Crucible Steel in Central Asia: Production, Use, and Origins

A dissertation presented to the University of London in fulfilment of the requirements for the degree of Doctor of Philosophy.

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Abstract

Central Asian crucible steel has been neglected in the scholarly literature in favour of Indian/Sri Lankan crucible steel (commonly called wootz). This is primarily because during the last few centuries Europeans frequently traded by sea, rather than via the overland route through Central Asia, with India and Sri Lanka where crucible steel was still being produced. The consequence of this was the assumption that the majority of crucible steel in Central Asia and the Middle East was imported from India and Sri Lanka. Moreover, the Central Asian crucible steel process is thought by many to be merely a variation of the Indian/Sri Lankan process. On the contrary, recently excavated archaeological evidence indicates that crucible steel was produced for centuries by a distinct process in various locations in Central Asia.

This dissertation presents the first detailed investigation of crucible steel in Central Asia. The characteristics of Central Asian crucible steel production were primarily determined by laboratory analyses of archaeometallurgical remains excavated from an early Islamic (9^{th}-10^{th} century AD) crucible steel workshop from Merv, Turkmenistan. A selection of crucible steel production remains from Medieval Uzbekistan was also examined. Furthermore, fifty-seven blades from three locations in Central Asia: Kislovodsk Basin, Upper Kuban River Region, and around the Aral Sea, were examined using metallographic analyses. The analyses identified four crucible steel blades, one of which may be the earliest known example of Damascus steel. The laboratory analyses supports early textual accounts of the use of crucible steel in Persia/Central Asia in addition to India, and the presence of blades with a Damascus pattern.

The results were compared to ethnographic reports, historical accounts, archaeological evidence, and replication experiments related to the production of crucible steel and Damascus steel blades. The results of the investigation clearly demonstrate the use of crucible steel in Central Asia for at least the past 1,500 years, and that it was being produced there for at least as long as it was produced in India and Sri Lanka.

Table of Contents

Table of Contents *continued*

List of Maps

List of Figures

List of Figures *continued*

List of Figures *continued*

List of Figures *continued*

List of Tables

List of Appendices

Preface

The discovery in the ruins of the Islamic city of Merv, Turkmenistan, of a large number of unusual ceramics, with black lids, white bases and a ring of a green glassy material, prompted this research. The subsequent identification of these ceramics as crucibles used for steel production during the late 9^{th} – early 10^{th} century AD which formed part of the author's MSc research, generated further interest in these remains and their importance in archaeometallurgy. This is of particularly interest, as crucible steel is commonly considered to have been produced mainly in India and Sri Lanka.

The overall purpose of the thesis was to examine crucible steel production and objects from Central Asia, including the association with crucible Damascus steel. Many unsubstantiated statements associated with Damascus steel appear in the scholarly literature. This did not favour a rigorous methodology from the outset. Instead, a number of avenues were investigated and followed as long as they continued to provide relevant information. How much additional information might be retrieved from these avenues with further research is assessed and discussed in the text.

Acknowledgements

First and foremost I would like to thank my Mother for her unending optimism, faith in my research, patience, emotional and financial support. I would like to send my gratitude to my supervisors, Prof. Peter Ucko and Prof. Thilo Rehren, whom I undoubtedly exasperated on more than one occasion. I also want to thank my past supervisors, Dr. John Merkel and Dr. Georgina Herrmann O.B.E. who introduced me to the remains. I would like to thank Olga Papakhristu for her generosity in sharing her knowledge of crucible steel production in Uzbekistan and providing samples for examination. I would also like to thank Irina Arzhantseva for her friendship, generosity and arranging for samples of blades to be taken in Russia. In addition I would like to thank James Allan, Brian Gilmour, and John Verhoeven for support and advice.

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Introduction

> *"There can be few other themes in the history of technology that have attracted so much romantic, carefree speculation. The romance may have kept wootz and related topics alive among textbook writers, but speculation is so common that any attempt at real research is almost sure to bog down.... The would-be student of the subject finds that a mountain of literature exists. A large part of this is speculative or even invented. Although another part may be reliable, the newcomer has no way of knowing which is which. He is accordingly cautious, and may decide to pass on to other, less confusing fields"* (Bronson, 1986, 15-16).

The term steel is used to denote a wide range of alloys, metallographic structures and compositions. From a metallurgical point of view steel is an alloy of iron with around 0.1 – 2% carbon. Steel is harder than iron, can be heat-treated and sharpened and is therefore excellent for the manufacture of knives, scissors, chisels, files and similar tools. Numerous processes can be used to make steel. The technology used in the production of crucible steel is very different than other pre-industrial methods of making steel. Apart from direct smelting to steel, pre-industrial steel was made in a hearth or furnace by either carburising (adding carbon to) wrought iron[1], a process commonly used in Europe and Asia, by decarburising (removing carbon from) cast iron[2], a method used in China, or it could be made in a crucible by either carburising or decarburising the crucible charge[3] (see Chapter 3 and 4).

Historical accounts testify that for at least a thousand years crucible steel was considered to be the highest quality steel, most notably because it was used to produce the so-called "Damascus steel" swords, famous for their attractive surface pattern, being tough, flexible and with the ability to retain a sharp edge (Bronson, 1986, 13). Crucible steel is generally attributed to production centres in India and Sri Lanka where it was produced using the so-called "wootz"[4] process and it is assumed that its appearance in other locations was due to long distance trade. Only recently has it become apparent that Central Asia was also a crucible steel producing region. The

[1] Wrought iron is iron with virtually no carbon.
[2] Cast iron is iron with a carbon content around 2 - 4%.
[3] Charge is the term used to denote the materials put into the crucible.
[4] Wootz is the English word for Indian crucible steel. Refer to Chapters 2 and 3 for details.

resulting questions include how crucible steel was produced and used in Central Asia, how Central Asian crucible steel processes and products compare to those of India and Sri Lanka, and how they relate to Damascus steel blades.

Despite an impressive amount of literature on crucible steel and related topics, particularly "Damascus" steel, very few scholarly papers have been published addressing the actual steps in making crucible steel in pre-industrial times. Bronson's quotation above highlights some of the problems associated with this research; a mountain of literature exists but much of it is speculation or invented, although, some of it may be reliable. Consequently, confusion exists in the literature about the relationships and differences between various crucible processes and products. Furthermore, in the scholarly literature specialised terms are widely used (e.g. "wootz"), although neither universally accepted definitions, nor criteria addressing the parameters of the definitions, have been set, resulting in misunderstandings and unfounded assumptions.

There is no doubt that historically Indian iron was an important commodity within and outside India. References to Indian iron occur in the literature of Classical authors. Indian iron was exported from the Classical period through to the Islamic period and later. Whether this Indian iron was crucible steel or another type of iron or steel remains uncertain. Bronson (1986) has dispelled many of the myths and assumptions that all "Indian iron" or "Indian steel" refers to crucible steel, as India produced iron and steel by other methods as well. Certainly crucible steel was exported from India at least during the 18th century. Evidence demonstrating that a significant quantity of crucible steel was also produced outside India, in Central Asia, for centuries is examined in the following chapters.

Although historical accounts of crucible steel production in Central Asia have been studied since at least the 1950s (Zaki, 1953-54; Zaky, 1955-56), physical remains of crucible steel production in Central Asia only began to be studied during the 1980s (Papakhristu, 1985). One of the aims of the research is to determine whether crucible steel found in Central Asia was an import from India, as many scholars imply (e.g.

Figiel, 1991, 7; Rostoker and Bronson, 1990, 127), or whether it was a native product, produced and used within Central Asian societies. Other aims include what materials and methods were used to produce the crucible steel, what the characteristics of Central Asian crucible steel objects are, where and when the technology may have originated. To reach these aims, evidence for the production and use of crucible steel outside of India has been sought. Historical accounts provided the first clues to its production in Central Asia; additionally, physical evidence for production was uncovered during the excavation of the crucible steel workshop at Merv, Turkmenistan, thus providing material for laboratory analysis. Furthermore, blades from western Central Asia were made available to address the use of crucible steel in the past. This research is significant because few remains of crucible steel production sites from Central Asia have been studied in detail, nor have criteria for the identification of crucible steel objects, as opposed to other steel objects, from Central Asian contexts been defined.

The dissertation is divided into two related topics: production remains and objects. Although the final crucible steel ingot made in India/Sri Lanka or Central Asia could be almost identical, the methods and materials used to produce the ingot were different. The ingot could be forged into virtually any shape, therefore it is necessary to distinguish between the ingot and objects made of crucible steel and those made of other types of steel. Only after the characteristics are determined can a link be made between the ingots and objects.

Remains from all known crucible steel production sites in Central Asia were investigated. The bulk of the research focuses on the examination of materials and techniques used to produce crucible steel at Merv, Turkmenistan during the early Islamic period (*c.* 800-900 AD). These were excavated by the International Merv Project, under the direction of Dr. Georgina Herrmann of UCL Institute of Archaeology, Dr. St. John Simpson, of the British Museum and Dr. K. Kurbansakhatov of YuTAKE (South Turkmenistan Multi-Disciplinary Archaeological Expedition). Remains of crucible steel production from Uzbekistan, broadly dated to the medieval period (9^{th} - 13^{th} centuries AD) were also investigated. Surface finds consisting of seven crucible fragments from Akhsiket, three crucible fragments from

Pap, a piece of a crucible product from Termez, and a crucible fragment from copper production at Kuva were all generously provided by Olga Papakhristu (Institute of Archaeology, Uzbek Academy of Science).

Ideally, swords associated with the production sites would have been studied, however, few archaeological swords survive from the regions despite centuries of pictorial and written accounts of their use. Swords and knives were selected because crucible steel is traditionally associated with "Damascus steel" swords. However, swords in museums in Turkmenistan and Uzbekistan could not be sampled and even if permission would have been granted, the swords are not well dated, primarily because they are chance finds or from unstratified contexts. One reason for this is because Zoroastrian and Islamic religions, which were practised in these areas, forbid the interment of goods with the dead and objects such as swords were too valuable to have been voluntarily disposed of as refuse. Therefore, swords and knives excavated from pagan burials in the northwest regions of Central Asia were examined. A total of fifty-seven swords, sabres, daggers and knives, of varying styles and time periods, were made available for study with the help of Irina Arzhantseva (Moscow State University, Jewish University of Moscow, and Russian Academy of Science). A total of thirty-seven blades from the Russian Northern Caucasus were examined: eighteen from the Kislovodsk depression, now in the collection of the Kislovodsk Local Museum, and nineteen blades from the Upper Kuban River Region, now in the collection of the Jewish University of Moscow. In addition, a total of twenty swords and knives from the Aral Sea region, now in the Russian Academy of Science, Moscow, were examined despite their extensive corrosion. All of the above objects were sampled in Russia for laboratory examination in London. The examination of blades revealed that four were made of crucible steel. A fifth blade was extensively corroded but also seems to be made of crucible steel. These crucible steel blades were examined to obtain data that could be used to study the relationship between the crucible steel process and the finished products, and to ascertain the characteristics of crucible steel objects from archaeological contexts.

Choice of Analytical Methods

Complementary methods of laboratory analyses were undertaken to determine the characteristic macrostructure, microstructure, and elemental components of the archaeological remains in order to produce data for comparison between modern and ancient materials and processes.

Characteristics are commonly determined by recording the physical appearance (e.g. stylistic studies), by establishing the elements present (e.g. material studies) and by establishing the particular crystal or grain structure (e.g. technology studies). Particular characteristics were used to classify and compare related objects or materials according to the principle that "the similarity of entities within groups does not occur by chance but reflects something inherently significant in their nature" (Rice, 1987, 274). Careful visual examination, with the unaided eye, of all the remains was performed to record their typical characteristic appearance (macrostructure) and to produce the initial classification of the types of materials.

The analytical method most appropriate for studying the microstructure of all the materials was standard light microscopy. Reflected light microscopy was used to examine the microstructure (e.g. texture and phases) of the slags and cross-sections of the crucibles. Reflected light microscopy uses normal incident linearly polarized white light that is reflected off a polished sample. Depending upon the crystallographic structure of phases in the sample, the light will reflect in a given manner that can be observed and compared to known textures, crystals and/or minerals. Corroded and preserved metallic remains (e.g. prills or objects) were also examined using reflected light microscopy and standard metallographic analyses. Metallography is commonly used in archaeometallurgy for examining metallic structures, identifying inclusions and estimating the carbon content of ferrous alloys (Scott, 1991, 57).

Crucible fragments were also examined using transmitted light microscopy and standard petrographic analyses. Petrography is a well established method, traditionally used to study rocks, which has been widely applied in the study of archaeological ceramics to determine the type, amount, and orientation of minerals, inclusions and pores present in the ceramic, based on the premise that ceramics are fundamentally artificial stones (Bamps, 1883 in Rice, 1987, 376).

Thin sections were ground and polished to a standard thickness of 30 microns. Plane polarised white light was transmitted through the sample. The light refracts and travels through different crystals at different speeds, dependent upon the crystal's particular structure. These different speeds can be observed when the light passes through a second polarizer (analyser). Each mineral will have its own characteristic features that can be measured using various tests and the results are compared to known minerals.

To estimate the number of inclusions in a given sample, a graph was laid over a photograph of a thin section of the crucible, taken in cross section (e.g. exterior glaze to interior slag). The number of squares occupied by inclusions was counted and compared to the total number of squares occupying the entire section. If the inclusions took up over half the area of the square, the square was considered "occupied" by the inclusion.

To distinguish the structural form of the mineral during petrographic analysis (particularly quartz because its form is temperature dependant), and to discover which minerals were present but too small to be observed using standard transmitted light microscopy, x-ray diffraction was employed. X-ray diffraction is a tool commonly used in geology and chemistry to determine crystallographic structures and has been applied to archaeological ceramics and to slags (see Rice, 1987; Bachmann, 1982). X-ray diffraction measures the lattice spacing between layers of atoms in crystals in a given material. The specific spacing is then used to identify unknown crystals by comparison with known crystals. The particular crystallographic structure can reflect the temperatures at which the crystal formed. This information can then be used to imply factors such as minimum or maximum firing temperatures.

Qualitative, semi-quantitative and quantitative analyses by Scanning Electron Microscopy equipped with an energy dispersive detector (SEM-EDS) and an Electron

Probe Microanalyser (EPMA) were used to determine the elemental composition of the remains. This information was used to identify the material, its particular behaviour characteristics and how the various remains relate to each other. These methods have been widely applied to material science and archaeological problems (e.g. Pollard and Heron, 1996).

The analytical methods best suited for establishing the elemental composition of the specific phases was EPMA. The main advantage of this technique was that the matrix and inclusions were specifically chosen and analysed separately, unlike methods of bulk analysis.

EPMA uses an incident electron beam that can be focused down to about 1 μm, on a specifically chosen spot, area, or across a line. The electron beam strikes the spot scattering different types of electrons in addition to creating an effect which produces x-rays (Pollard and Heron, 1996, 50). The products that are of particular interest are the secondary electrons, backscattered electrons, and characteristic x-rays. Secondary electrons are used to produce high magnification topographic images of the sample. Since electron waves are smaller than light waves they can be used to observe the surface texture at higher magnifications than ordinary light microscopy. The backscattered electrons produce an image of the varying elemental compositions. Phases with different average atomic numbers are observed as dissimilar shades of grey because compounds with higher average atomic numbers reflect more backscattered electrons than those compounds with lower average atomic weights. Therefore, phases could be identified and specifically selected for analysis.

Characteristic x-rays were used to determine the elemental composition. This energy was detected and measured using energy dispersive spectroscopy (EDS) or wavelength dispersive spectroscopy (WDS). Both EDS and WDS have good precision (reproducibility of the measurement), however WDS has higher accuracy (closeness of the measurement to its true value) and a lower detection limit (the limit down to which a signal can be distinguished from background signal at a specified confidence level), than EDS (Potts, 1987, 1).

In addition to detection limits, the time required to analyse a given sample was considered. The length of time needed to analyse a given sample using WDS depends on the number of crystals available in the particular machine and the number of elements that are being analysed. On average, one WDS analysis of a ceramic phase was about fifteen minutes. On the other hand, because EDS measures all the elements at one time, the time required is not dependent on the number of elements present or analysed and an area could be analysed in about two minutes. Consequently, EDS is faster but has a high detection limit, whereas WDS can detect elements, which appear in lower quantities, but requires more time, therefore both methods were used. The choice depended upon how accurate the measurement needed to be for the questions being asked.

The accelerating voltage (KV) chosen for EPMA depended upon factors including the elements analysed for, the estimated quantity of these elements, and the material being analysed. Lower KV is better for lighter elements, whereas a higher voltage is used for heavy elements or elements which are present in very small quantities. This is because when using a relatively high voltage, such as 20 KV, some light elements are easily excited and can migrate to areas out of the detection area (such as sodium in glass samples), but the voltage is high enough to sufficiently excite the heavy elements so their x-ray fluorescence can be detected. If a lower voltage is used, such as 15 KV, the detection limit is lower but a more accurate measurement of light elements is achieved.

Another consideration was the size of the area that was being analysed and fluorescence effects. Due to fluorescence effects, the smallest length that could be analysed, with relative certainty was about 5 μm. Another consideration was the phases in and around the point in question because the depth of penetration of the primary electrons is inversely proportional to the density of the material being analysed and the energy of the beam (KV), therefore the area below and around the desired phase may also be contributing to the recorded composition if the depth of the phase is below the depth of penetration.

A JEOL Superprobe JXA-8600 and a Hitachi Scanning Electron Microscope S570 housed in the Institute of Archaeology werc used for the majority of the analyses. A JEOL Scanning Electron Microscope housed in UCL/Birkbeck (UL) Geology Department was also used early in the study because it was already prepared for the analysis of petrographic thin sections. Each machine was equipped with a computer program for ZAF corrections (Z is atomic number, A for absorption and F for fluorescence effects), for accurate quantitative analysis (Watts, 1985, 188).

Sampling Procedure

Ideally, all existing evidence of the process in question should be represented in the chosen samples. There are three general methods of sampling, "representative", "random", and "exotic" (Feuerbach and Merkel, 1998). "Representative" sampling requires one to examine a large bulk (ideally all) of the finds and to choose those samples characteristic of the majority of finds. "Random" sampling requires one to indiscriminately gather samples to reducing bias. The selection of items, which appear, in some way, to be different or unique is "exotic" sampling. The author, for examination of the Merv remains used each of these approaches. The limited number of remains provided from other locations did not require a choice; all available samples were studied.

All samples were removed using a portable Plas-Plug electric water-cooled tile-cutting saw with an ultra-thin diamond impregnated blade. All samples, apart from those taken for transmitted light petrography and XRD, were mounted in cold setting plastic resin. This allowed the samples to be easily ground and polished, prevented the loss of corroded or deteriorated edges, and prepared the samples for reflected light and electron microscopy. The thin sections were mounted on glass slides using Petropoxy resin. All samples analysed by electron microscopy were polished flat prior to analysis and carbon coated to produce a conductive layer. All samples were ground and polished using standard methods (Bousfield, 1992) except the samples for XRD that were given to UCL/Birkbeck (UL) geology department for processing and analysis.

The remains from Merv and Uzbekistan were already fragmentary when collected. From each category of remains, samples were taken from representative fragments. Whenever possible, the sample exhibited more than one feature (e.g. slag attached to the crucible wall). This allowed the relationship between different features to be studied and reduced the number of samples needing to be prepared. The number of samples analysed depended upon the number of original fragments, the homogeneity of the structures and composition between various samples of a given material when examined using light microscopy and preliminarily analysed by SEM- EDS.

The majority of blades were complete therefore to minimize damage to the object only a small V shaped cross-section was removed from the blade near the handle. Larger or complete cross-sections were taken from broken or incomplete swords. After the samples were etched and examined, they were re-ground and polished for microprobe analysis to assure that the etching did not affect the elemental composition.

Setting and Brief History of Central Asia

Central Asia is a vast region of barren deserts, fertile oases, steppe zones, and metalliferous mountain ranges. It is generally defined as the area that is now occupied by the countries or regions of Afghanistan, Western China, Northern India, Iran, Southern Russia, Pakistan, South-western Mongolia, Kazakhstan, Turkmenistan, Kyrgyzstan, Uzbekistan, and Tajikistan (Map 1).

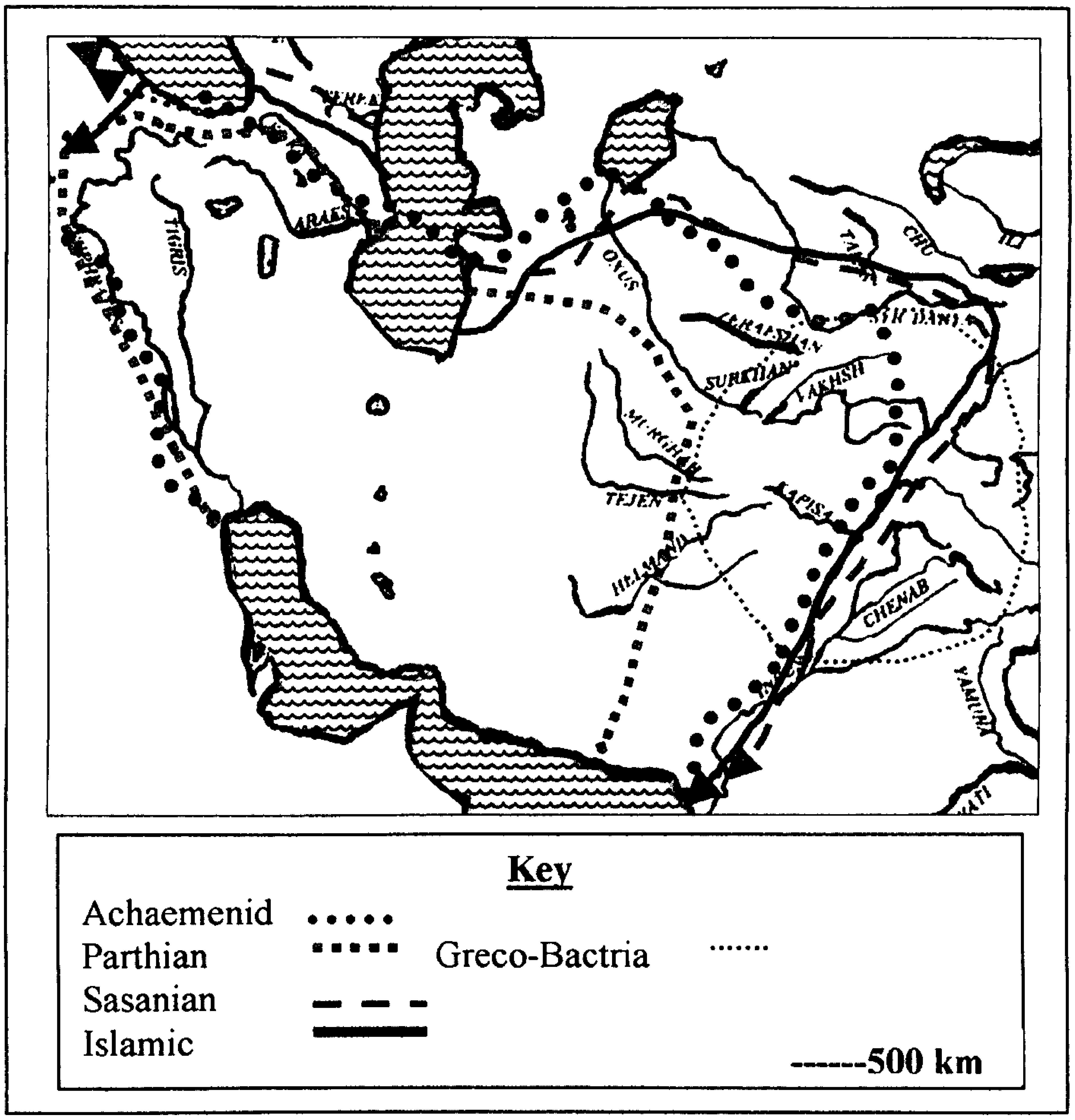
Map 1: Location of Central Asia and Modern Countries.

Some civilizations built cities in the foothills and oases while nomadic civilisations travelled the steppe zones in the north. The mountains and the deserts provided a barrier between cities but were routinely crossed after the establishment of numerous outposts, such as the desert caravanserais, each a day's travel from each other.

These cities and outposts formed the so-called Silk Road. The Silk Road was a network of routes along which trade items, and consequently ideas, travelled back and forth, both east-west and north-south. Goods reached at least as far as China, Italy, Sri Lanka, and the Ural mountains (Litvinsky and Guang-da, 1996, 31). Although the Silk Road connected the greater Central Asian region, and made available goods from distant lands, the development of local traditions continued.

The political situation and development of ancient Eastern Central Asia is not well understood. Whether organized states existed in the regions of Bactria, Margiana, Sogdiana and Chorasmia before Achaemenid times is hotly debated (see Dandamayev, 1994, 41-42). The Achaemenids (558 BC - c. 250 BC), an Iranian-speaking people from Persia, are accredited for establishing the first Central Asian empire. They ruled lands from the Mediterranean Sea to the Indus river valley, to the Persian Gulf to the Aral Sea, virtually laying the political boundaries for the subsequent Parthian, Sasanian and Islamic empires (Map 2). From the sixth century until the third century BC Central Asia and Northwest India to around the Indus River, were under the same administration. It is the Achaemenids who are usually associated with the widespread use of iron, and the control of natural resources (Pigott, 1985, 626). Local iron working traditions before the arrival of the Achaemenids in Eastern Central Asia have not been investigated.

During the 4th century BC Alexander the Great invaded Iran and parts of Northern India resulting in the Greek-Macedonians as rulers. After the death of Alexander the Great, one of his officers, Seleucid I, rose in power and consolidated his rule in Central Asia and India up to the region of the Hindu Kush (Dani and Bernard, 1994, 89). In the eastern lands the Greco-Bactrian kingdom continued to rule until the 130's BC when nomadic tribes conquered the region and established the Great Kushan Empire. In Iran, Greek-Macedonian rule succumbed to the Parthians (c. 250 BC - AD 224). During the mid-third century BC, however, the Parthians gained control over Central Asia but not India, which was now controlled by the Mauryans' who conquered lands up to the Iranian plateau (Dani and Bernard, 1994, 90). Parthians were great traders, using their territory to control the flow of goods from India and China to the Roman world, the main path of the Silk Road (Wiesehöfer, 1996, 147).



Map 2: Approximate Locations of Past Political Borders.

For the next few centuries the lands around the Indus River belonged to either Indian or Central Asian empires. The Sasanian dynasty succeeded the Parthian Empire in 224 AD. The relationship between Sasanians and Kushans is not well understood. What is known is that the Kushan Empire became a vassal kingdom under the Sasanians during the reign of Ardashir I (died 241) forming what is called the Kushano-Sasanian kingdom. The Sasanian Empire ended with the Arab invasion during the 7^{th} century AD, beginning the Islamic period. The archaeometallurgical remains of crucible steel production in Central Asia date to this period. The so-called Islamic period ends with the Mongol invasions during the 13^{th} century.

Chapter 1: Crucible Steel Production in Central Asia

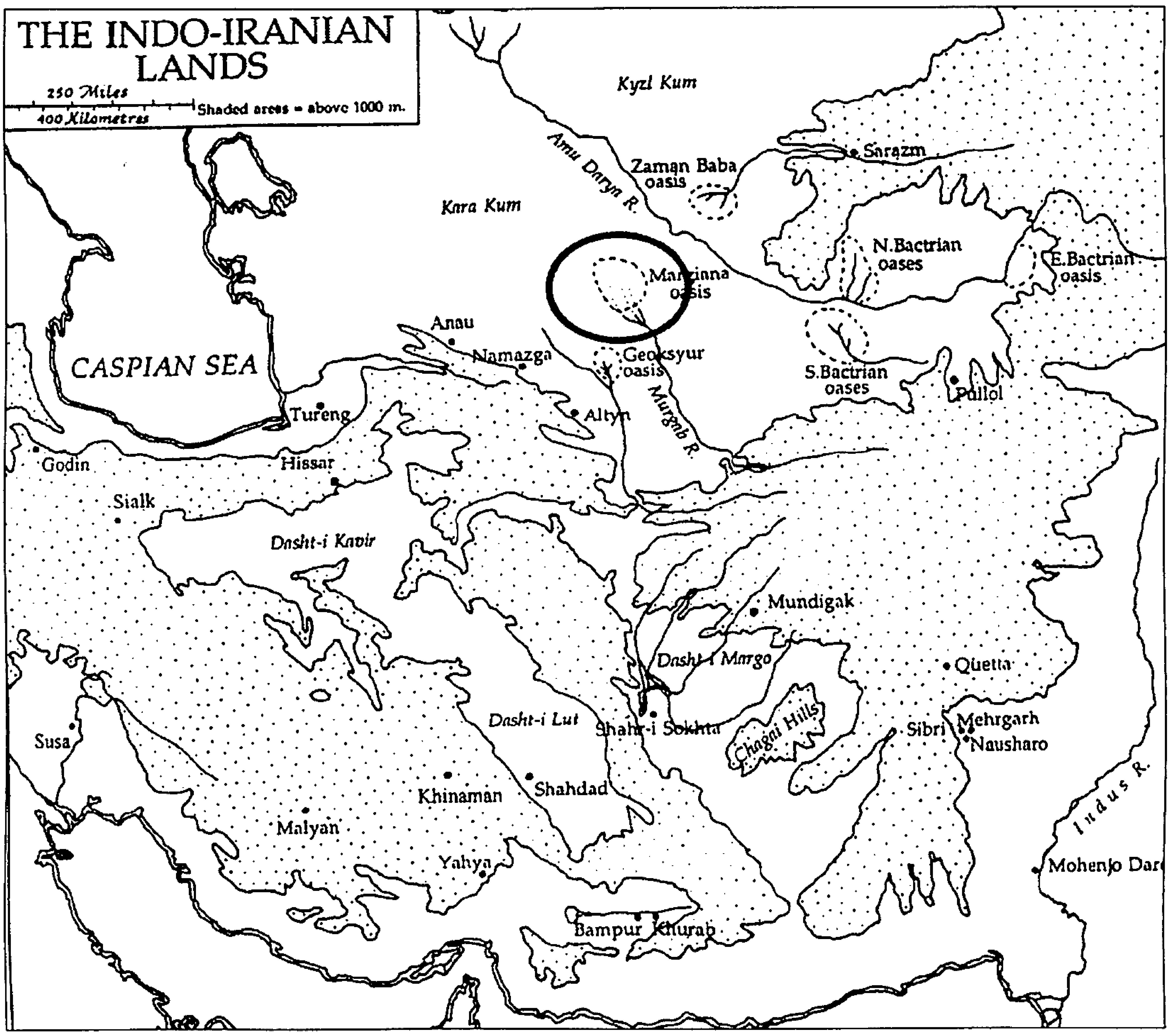
> *"Hard crystals I anatomize,*
> *and iron and steel too,*
> *and stubborn rocks I shave and grind,*
> *and look them through and through"*
> (Sorby, 1863)

The bulk of samples used to determine the characteristics of crucible steel production in Central Asia are from the late 9^{th} – early 10^{th} century, excavated at Merv, Turkmenistan. Remains from crucible steel production in Uzbekistan were also examined to compare with those from Merv, and to begin to determine the range of materials and techniques used to produce crucible steel in Central Asia. Once the characteristics were determined, the remains were considered in a broader context in order to understand how they relate to other technologies and crafts used within the society. The implication is that crucible steel production in Central Asia was a developed technology, at least by the late 9^{th} century AD if not earlier. The processes varied between different locations and the methods and materials shared common features with other local craft traditions.

Archaeological Remains from Merv, Turkmenistan

Setting

At the southern edge of the Kara Kum desert in the Merv oasis, numerous small towns and cities formed. Classical writers called the region Margiana. The cities were irrigated by the Murghab River, which flows northward from the mountains in Afghanistan (Map 3).

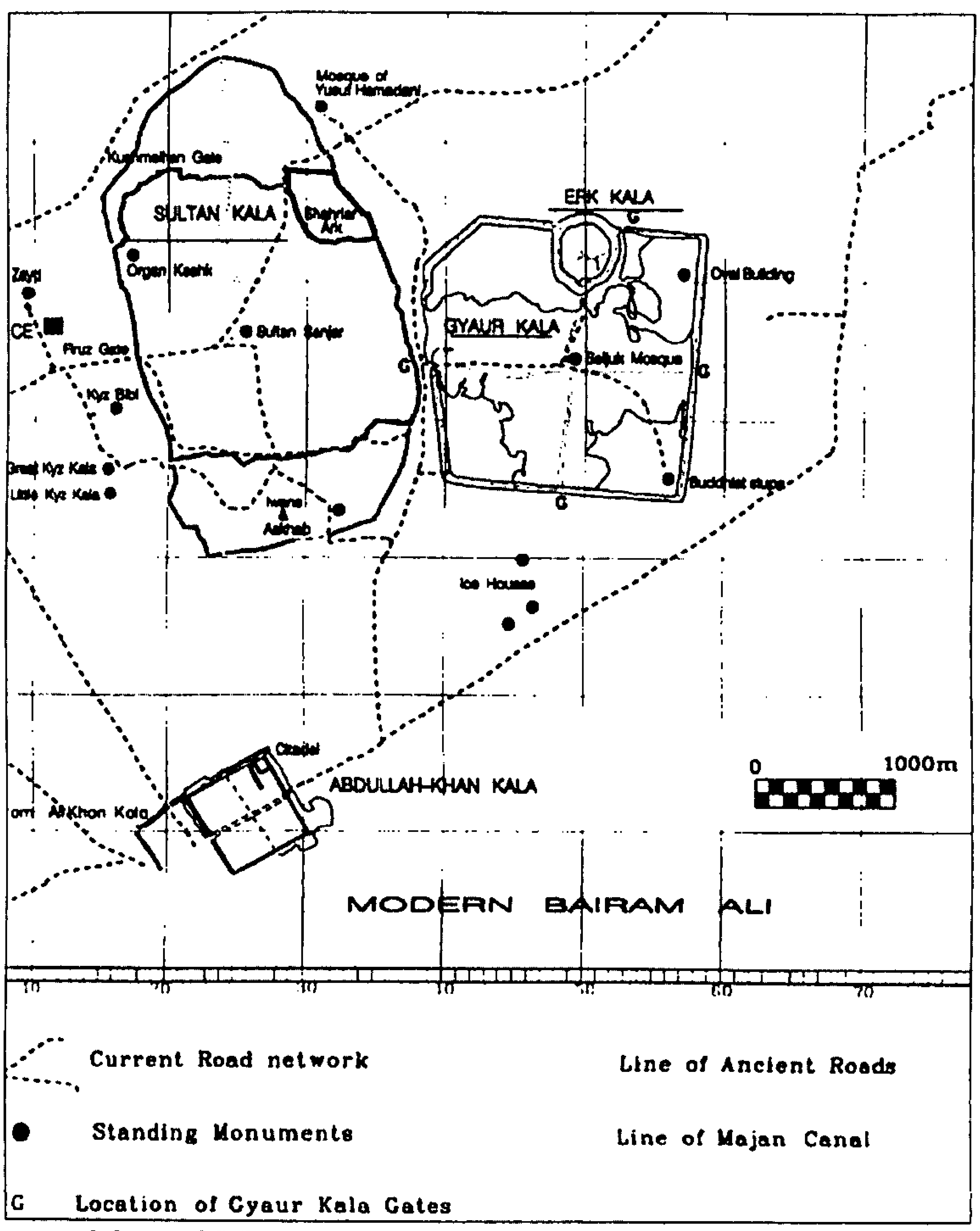


Map 3: Region of Margiana and Bronze Age sites
Adapted from Hiebert (1994, 13).

During the so-called Bronze Age, Merv was part of the Bactria-Margiana Archaeological Complex (BMAC). The name denotes similarities of finds and settlement patterns between the regions of southeastern Turkmenistan and parts of Uzbekistan (Hiebert, 1998, 152). There is an overall lack of research on the material remains from the period of the Late Bronze Age (1750-1500 BC) to the so-called

Early Iron Age (1500-1300 BC). In Bactria-Margiana the term Iron Age reflects a change in the material culture not necessarily the appearance of iron tools. Little research has been undertaken on any aspect of the Iron Age in Margiana. Early Iron Age Margiana is characterized by the (so-called) Yaz culture (Hiebert and Killick, 1993, 187) and there are some similarities in finds, notably pottery, of the Yaz I culture with that of northwest Iran, particularly Tepe Sialk B (Genito, 1998, 90).

The first firm mention of Margiana in Achaemenid texts is from 522/521 BC (Nikitin, pers. com.). Around this time, the first of the three cities that comprise ancient Merv (Map 4), now known as Erk Kala, was founded, and Zoroastrianism is thought to have been the dominant religion (Sarianidi, 1998). The founding of the second city, now called Gyaur Kala, corresponds with the establishment of the Persian Empire (250 BC - 224 AD). The city was then called Antiochus Margiana and inhabitation continued throughout the following Sasanian period (224 AD - 651 AD).



Map 4: Three cities of Merv mentioned in the text: Erk Kala, Gyaur Kala and Sultan Kala. Abdullah-Khan Kala is a later city.

Following the Sasanian period, Merv was incorporated into the Islamic Empire when Khurasan fell to the Arab invaders and Zoroastrianism gave way to the new religion, Islam. Khurasan was the Islamic name given to the region that contained the cities of Merv, Nishapur, Balkh and Herat. This made Merv one of the easternmost outposts of the Islamic world and again secured its strategic position along the Silk Road. A large military garrison was stationed at Merv, both to defend the region from various invading Turkic and Mongol tribes, as well as for invasions into north India and Bactria. During this period, the city flourished in the arts and sciences attested to by many of the creations which can be found in large museums. A new city, now called Sultan Kala, was built to the west of Gyaur Kala. A proportion of the population moved out of Gyaur Kala into the new city. The archaeological remains indicate that Gyaur Kala became the industrial area with numerous workshops specialising in metalwork and other crafts.

Metallurgy at Merv

At several sites in the Merv Oasis, evidence, such as moulds and crucibles, from the Early Bronze Age (2100-1900 BC) and the Middle Bronze Age (1900-1750 BC) have been excavated suggesting indigenous metalworking from an early period (Hiebert, 1998). During the Early Bronze Age there was a change in the type of copper-alloys used, from bronze in the earlier period of Margiana 1 to arsenical and leaded copper alloys in Margiana 2. This change coincides with an increase in cultural similarity from the Kopet Dag region to that of Bactria (Hiebert, 1994, 160). Bronze appears again during the latter part of the Middle Bronze Age and its use increases during the Late Bronze Age (1750-1500 BC). The metallurgical remains from Margiana indicated a process of casting copper alloys then working and annealing (Hiebert, 1998; Hiebert and Killick, 1993; Hiebert, 1994, 160). The analysis of non-metallic inclusions in Bronze Age copper-alloy objects by Hiebert and Killick (1993) indicated sulphides, suggesting the smelting of copper sulphide ores possibly with an iron flux.

Information on smelting or metalworking traditions of South Turkmenistan post Bronze Age until the early Islamic period is absent. The author, however, examined eight pieces of Sasanian period iron excavated at Merv. The pieces were found to be either wrought iron or too corroded to confidently determine the type of iron alloy.

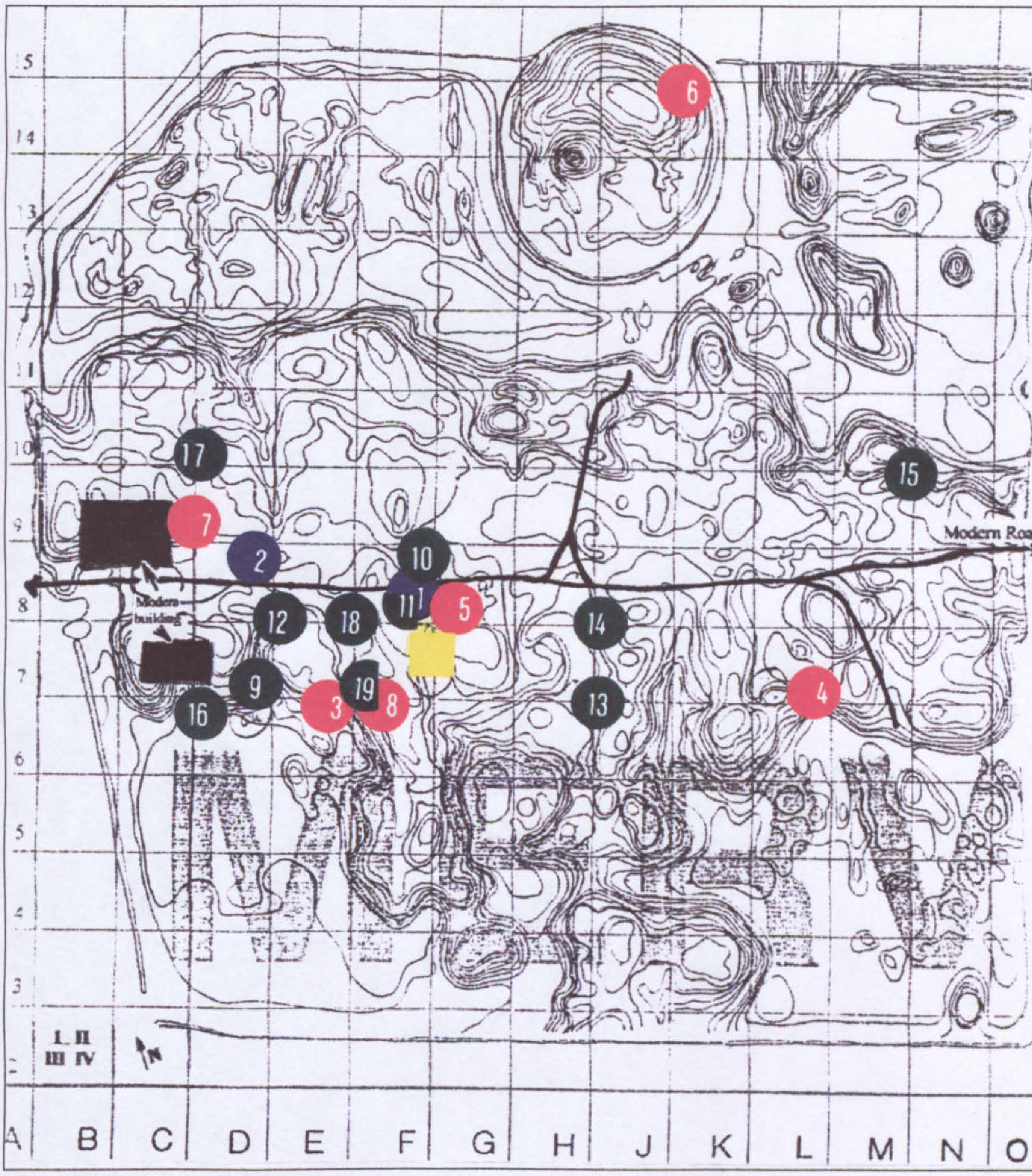
The successive cities of the Merv oasis have a long history of metallurgy although there are no local sources for ores or refractory clay known to be present in the oasis. Plutarch mentions the use of Margiana's (Parthian Merv) steel to make armour for soldiers (Plutarch, 1915, 387.) Also under the Parthians, during the first century AD the city minted coins (Litvinsky *et al.*, 1994, 481; Koshelenko and Pilipko, 1994, 140). During the Sasanian period "between 240 - 260 (AD), the Merv ruler minted in his own name a bronze coin with the figure of a horseman..." (Litvinsky *et al.*, 1994, 481). "Iron blooms were discovered in many settlements and an arms workshop dating to early Sasanian times were found in Old Merv itself" (Litvinsky *et al.*, 1994, 483), but the writer of this dissertation has not seen any evidence of this. It seems more likely that these "blooms" were smithing hearth bottoms, although actual blooms might also have been discovered (see below). There was a mint at Merv during the post-Sasanian period and during the Islamic period (Herrmann *et al.*, 1994, 63-65).

The region of Khurasan is mentioned specifically as a steel-manufacturing centre by the Islamic scholar al-Kindi (c. 801-866 AD) (Bronson, 1986, 19). During the 9th century the Khurasan was known for manufacturing swords made of local iron and iron from Sarandib, modern Sri Lanka (Al-Hassan, 1978, 34). During the 10th century the region produced weapons and breastplates (Allan, 1979, 69). Marv [*sic*] is mentioned by al-Muqaddasi (late 10th century) as producing "nahas" (Allan, 1979, 128) which is translated as either copper or a low tin bronze (Allan, 1979, 126). Textual and archaeological evidence clearly show that for centuries Merv was an important metalworking centre, despite the fact that all metals and associated raw materials needed to be imported into the city.

Discovery and Location of the Industrial Area

The International Merv Project excavated Merv from 1992 until 2000. During the initial surface survey, Bettina Stoll-Tucker and David Tucker identified within the walls of Gyaur Kala concentrated areas of high temperature industrial debris, apparently *in situ* (Map 5). The coins and domestic ceramics excavated alongside the remains date the workshop to the early Islamic period, late 9th - early 10th century (Herrmann *et al.*, 1997, 15). Some of the industrial debris was brought to the UCL Institute of Archaeology for initial identification. The laboratory investigation indicated that there were many workshops specialising in different types of copper alloys, iron, and steel (Table 1). The distribution of concentrated areas of remains indicates many individual workshops. In some workshops different types of copper-alloys were being processed, most notably leaded copper alloys and brass. The presence of what might be copper smelting slag is interesting because ores are not found close to Merv. Smelted, but not refined metal may have been imported into the city.

The area chosen for full excavation (MGK 4) provided primary source material for the investigation of materials used for the production of crucible steel.



Key

Miscellaneous finds

Copper-alloy processing debris

Iron/steel processing debris

MGK 4: Crucible steel workshop

Modern buildings

(#) Location of remains

Scale 1 square = 150 m x 150 m

Map 5: Merv Surface Survey.

Table 1: Surface Finds

Number on Map	Location Code	Material	Method of Analysis
Miscellaneous			
1	NE of G.8/S of road	Yellow powder	SEM/EDS
2	8.D.II	Glass	Probe
Copper-alloy debris			
3	6.E.II	Cru, Cu Slag,	SEM/EDS
4	7.L.IV	Cu	SEM/EDS
5	8.G.III	Cu	SEM/EDS
6	14.K.I	Cru, Fe, Cu	SEM/EDS
7	G.20	Cu	SEM/EDS
8	G.59-14 Furnace site	Slag, Cu	SEM/EDS
Iron and steel debris			
9	7.D.IV	Slag, Fe, Cu	Visual
10	8.F.II	Fe slag	Visual
11	8.F.IV	Fe slag	Visual
12	G.22-23 slag heap	Fe slag(?)	Visual
13	G.32	Slag, Fe	Visual
14	G.37 (20x20)	Slag, Fe	Visual
15	G.42	Fe	Visual
16	G.50 20x20	Slag, Fe	Visual
17	G.54	Slag, Fe	Visual
18	G.58	Slag, Fe	Visual
19	G.59	Fe slag	Visual

Key

Cu	= Copper alloy debris
Fe	= Iron/steel debris
Cru	= Crucible fragments
Glass	= Cullet?
Slag	= Metallurgical waste
Fe slag	= Iron processing slag
Visual	= Unaided eye
SEM/EDS	= Scanning electron microscope with energy dispersive spectrometer
Probe	= Electron microprobe equipped with wavelength dispersive spectrometer

The Excavation of the Crucible Steel Workshop

In 1993 Dr. John Merkel began the excavation of the site (samples labelled MGK 4), by undertaking a "surface scrape" of an area of about $2m^2$ (samples labelled 7.F.II) (Figures 1, 2 and 3). From 1994-1996 other members of the International Merv Project performed excavations at MGK 4 D. Connolly led the 1994-95 excavations and J. Steadman led full-scale excavation of the workshop in 1996. For preliminary reports on the excavations see IRAN (Herrmann *et al.*, 1993; 1994; 1995; 1997). The author participated in the 1994 and 1996 excavations.

The excavations uncovered numerous structures including mud brick walls and furnaces, in addition to ceramics, coins, copper alloy debris, glass fragments, slags, ashes, corroded iron alloy fragments, charcoal and environmental remains such as animal bones and seeds. Ceramic pieces were classified on site into domestic and industrial by visual inspection. The author investigated the slags, crucibles and debris from high temperature processes, whilst non-industrial remains were given to other specialists for investigation (Forthcoming excavation reports and preliminary reports in Herrmann *et al.* 1993; 1994; 1995; 1997). The majority of remains were found in an area with a high concentration of crucible fragments and furnace debris, the so-called crucible pit. Surface finds which were possibly related to iron processing, as they were magnetic, were also collected from adjacent piles of debris (Appendix A).

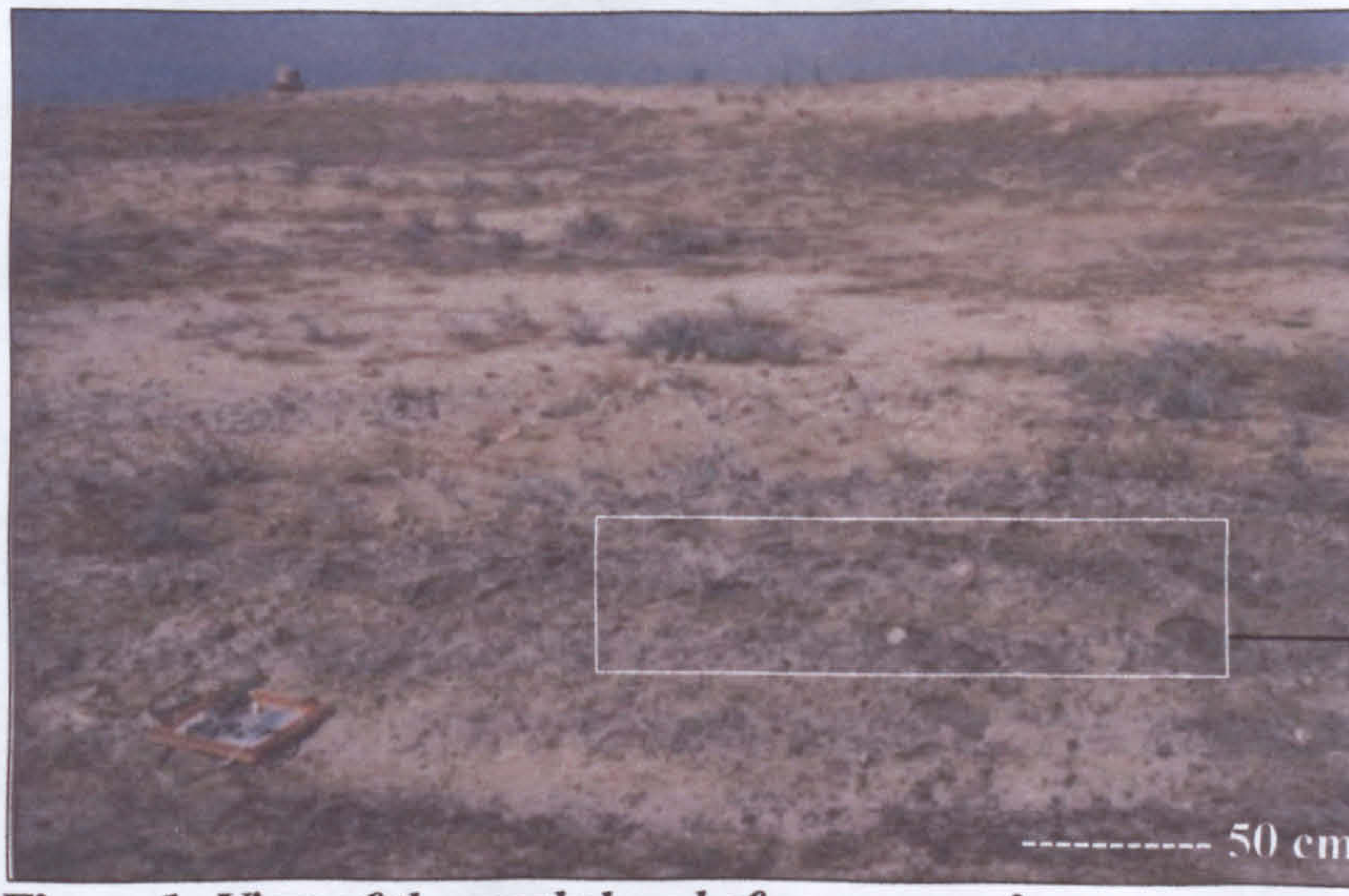


Figure 1: View of the workshop before excavation.

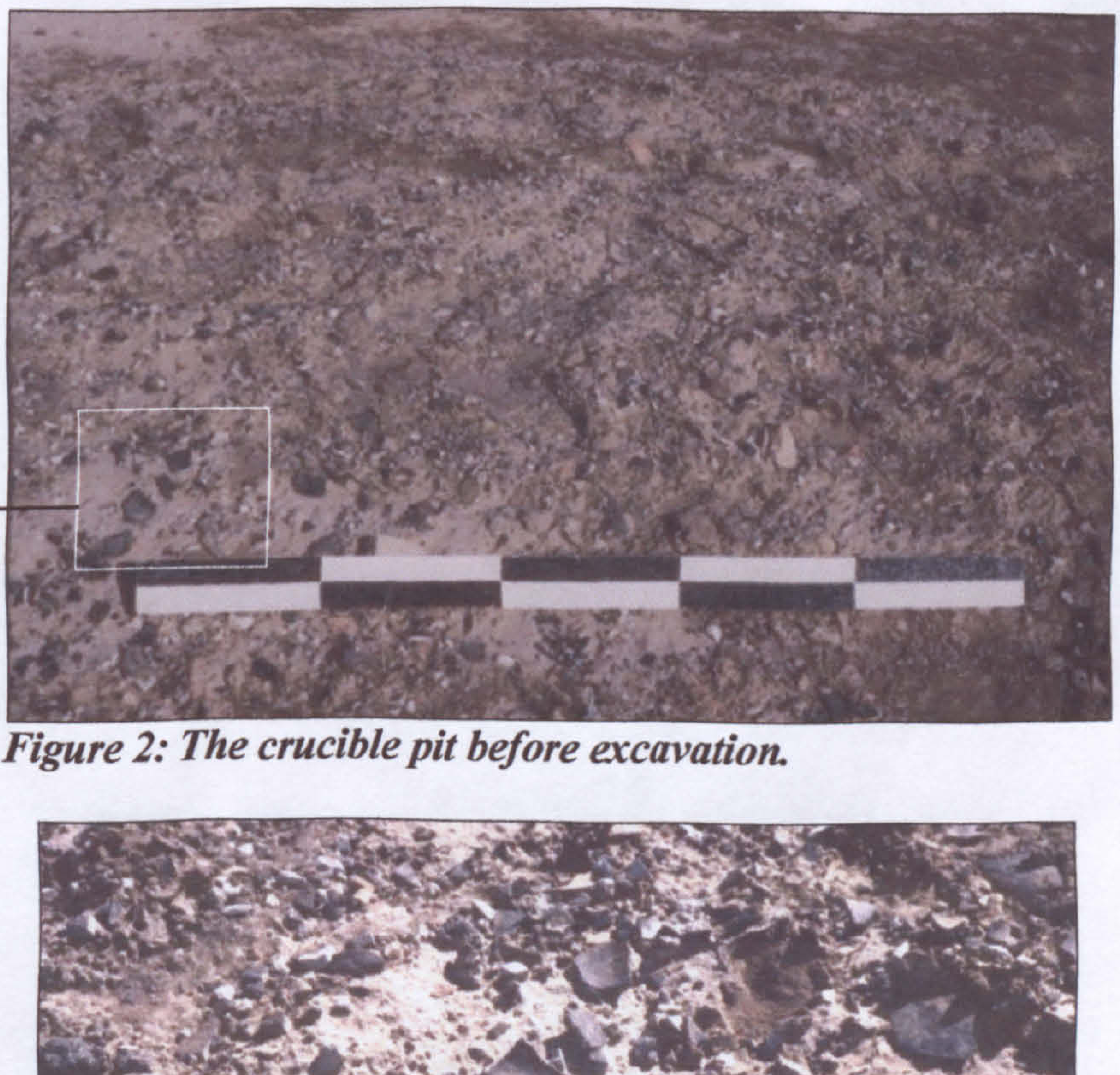


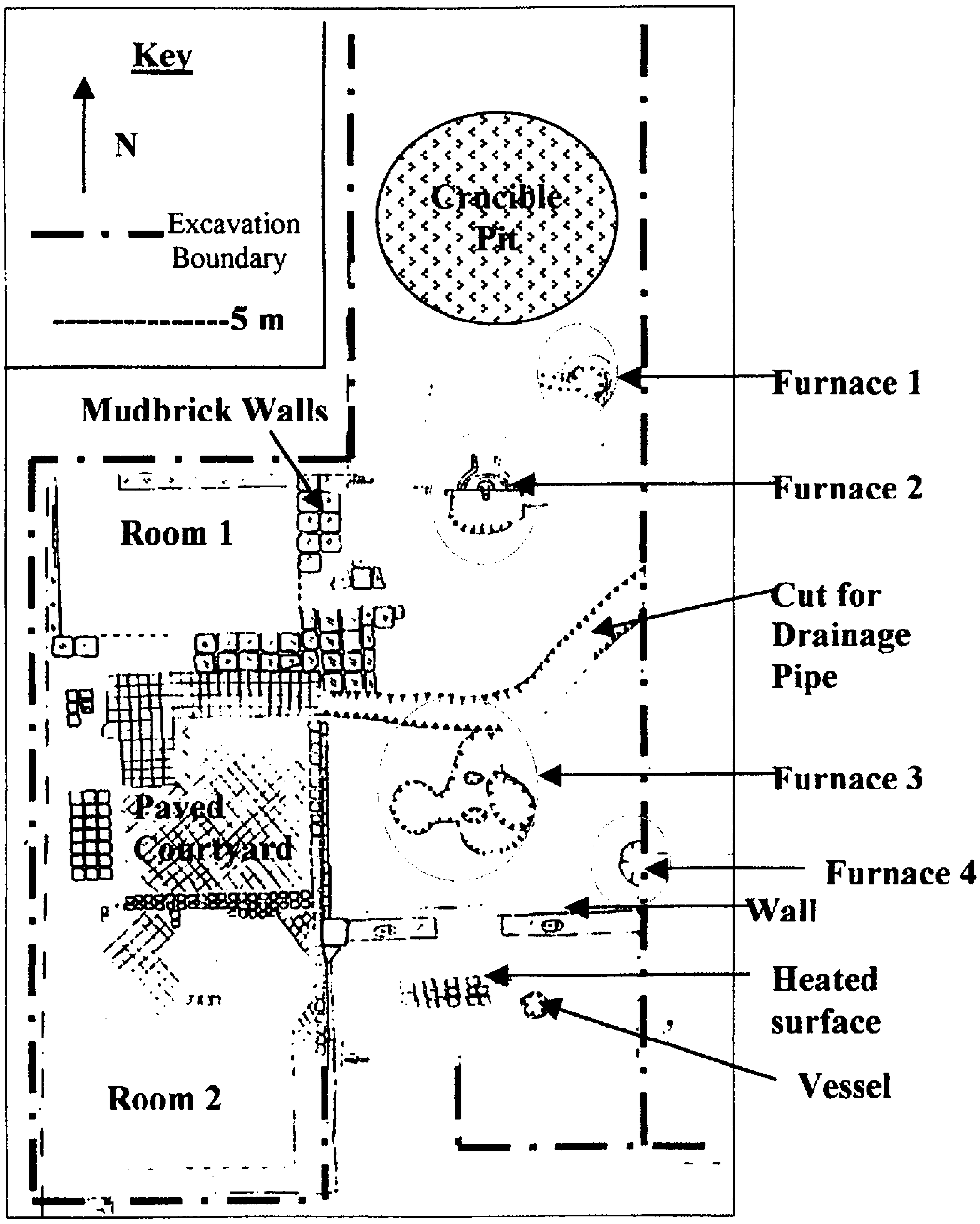
Figure 2: The crucible pit before excavation.

Figure 3: Detail of the crucible pit.

The excavation zone known as MGK 4 consists of two separate areas: the area adjacent to the "hollow way" (the ancient east-west road running through Gyaur Kala), and the industrial area set back a few hundred meters south of the "hollow way". Only the industrial area is discussed here. The excavation uncovered part of the industrial area of the workshop in addition to adjacent domestic housing, presumed to belong to the craftsmen's families. The full extent of the workshop and domestic area is unknown because only an area roughly 20 m^2 was excavated. Turner and Powell (forthcoming) identified twelve phases of activity. The workshop was not excavated down to non-industrial layers. Turner and Powell (forthcoming) suggest that crucible steel debris found in the earliest excavated phase indicates that earlier phases of industrial activity may be found at lower levels.

The workshop and domestic area consists of various rooms and a courtyard but the excavations did not reveal the complete extent of either (Map 6). The courtyard is lined with fired bricks in a diamond pattern with a border (Figure 4). The courtyard is *c*. 5 m x 5 m and the bricks are all 18 cm^2 (Turner and Powell, forthcoming). In the northeast corner of the courtyard there is a drainage pipe, which descends below the floor of the workshop and terminates in a soak-away. Presumably the pipe was used to drain off rainwater falling into the open courtyard. A wall separates the presumed domestic area and courtyard from the workshop.

The workshop can be roughly divided into three areas. The area of the crucible pit, the area of the furnaces, and an area separated from the other areas by an east-west running wall. The crucible pit was found in the north of the workshop. Next to an enclosed domestic room adjacent to the open courtyard, four furnaces were found and each was located with secondary structures, either a hut or a protective wall (Turner and Powell, forthcoming). In the third area, a raised mud brick workbench was found (Figure 5). Some of the mud brick tiles exhibited an orange colour and friable top surface suggesting they were subjected to heat, presumably caused during metalworking. At the southeast corner of the bench, placed in a cut in the ground, was a ceramic vessel with the opening at what was the ground level during the use of the workshop. The original content and purpose of the vessel is unknown but it may have contained a substance needed during the metalworking process.



Map 6: Plan of MGK 4 excavation
(based on Turner and Powell, forthcoming).

The proximity of the domestic dwellings to the industrial area, together with the relatively small number of furnaces and the quantity of industrial remains indicated a permanent workshop, possibly run by a family. There appears to have only been two phases of construction and the comparatively shallow depth of deposits suggest that the workshop was in use for less than a century and probably closer to fifty years.

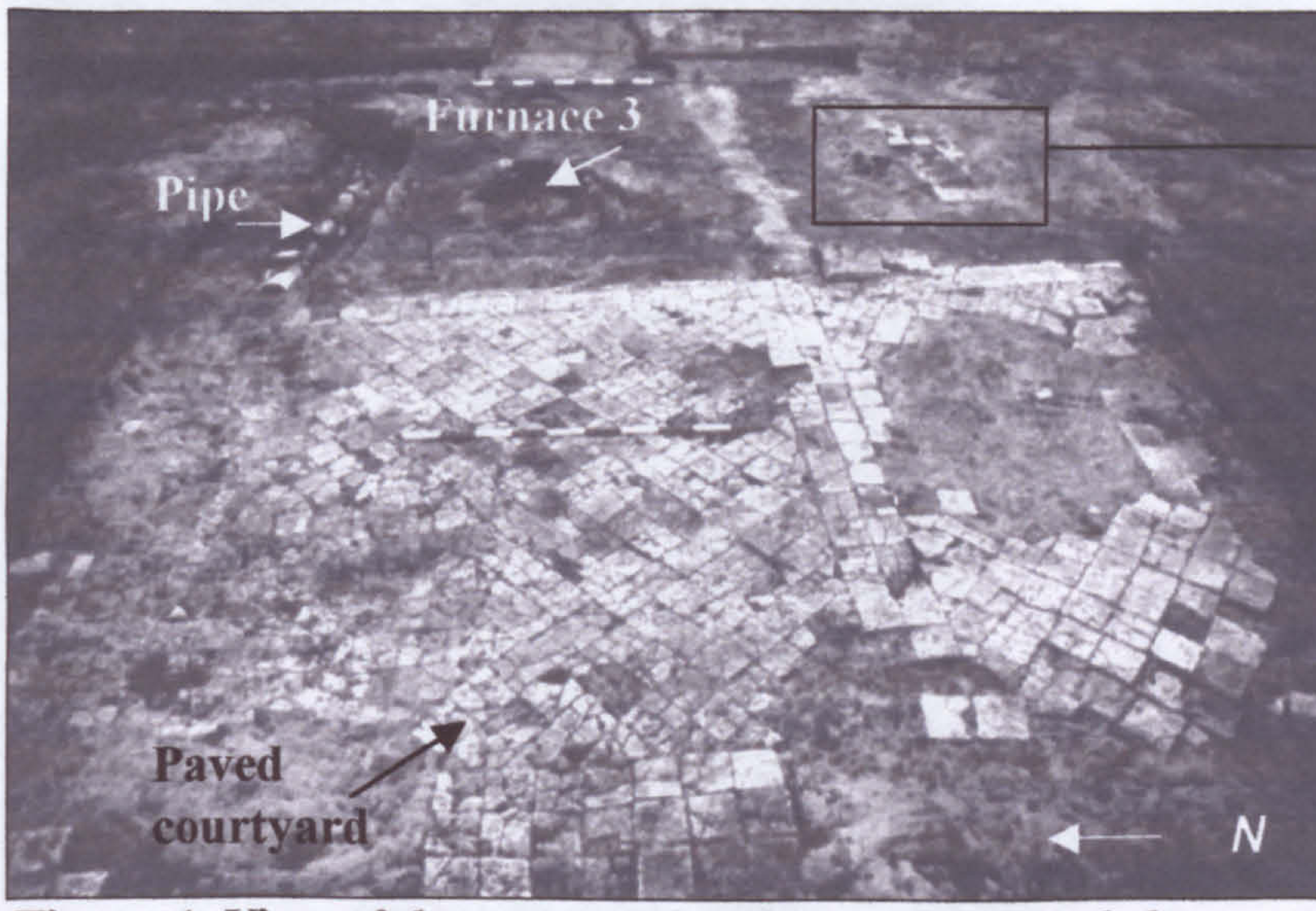


Figure 4: View of the courtyard and part of the workshop (2 meter scale).

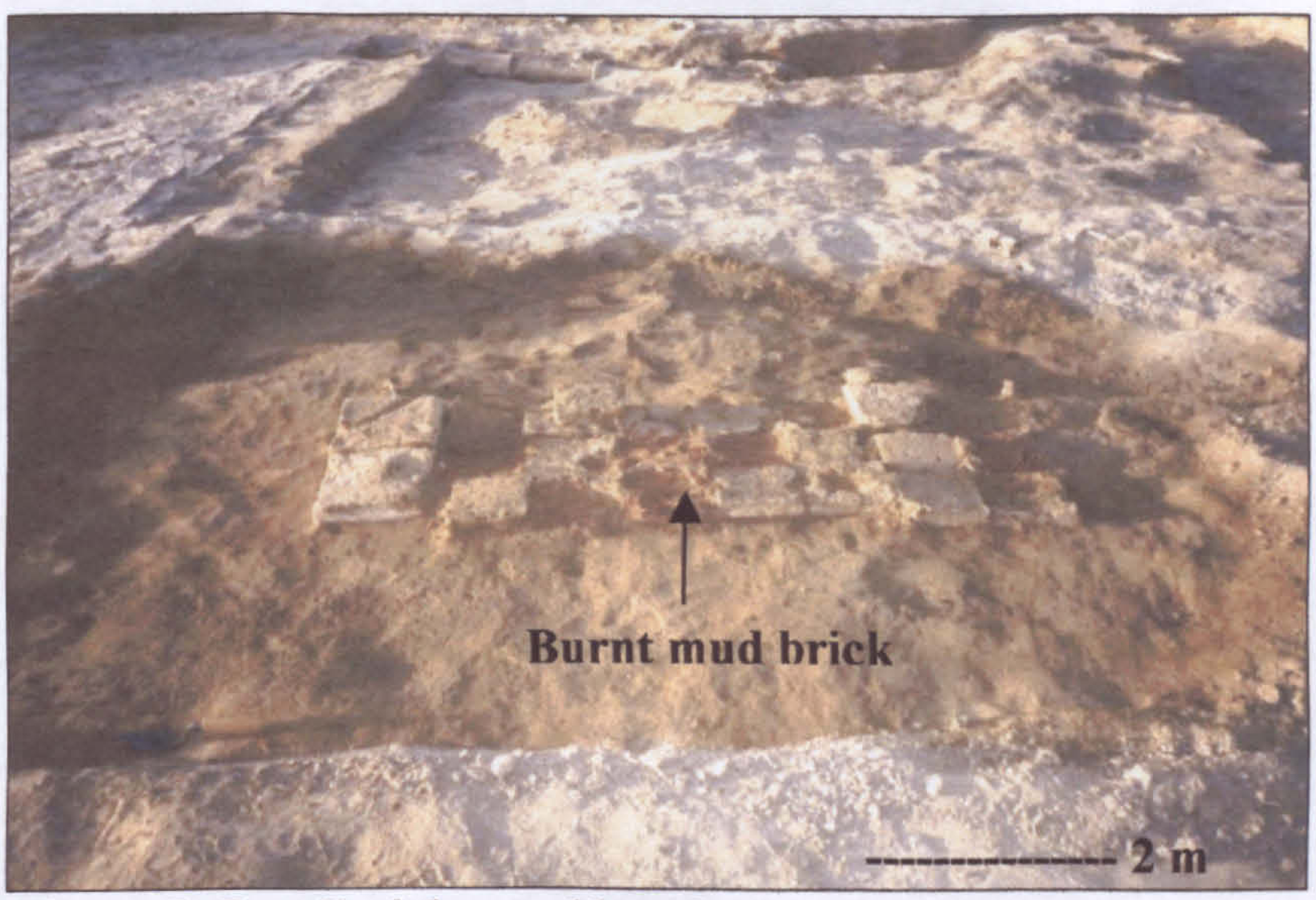


Figure 5: Detail of the workbench.

The examination of the domestic ceramics by David Gilbert (pers. com.) indicated that plain wares were the most common type of domestic ceramic found during the excavation of the crucible steel workshop and the adjacent domestic dwellings. In addition, there were a variety of glazed and painted ceramic wares. Residual Sasanian ceramics were also uncovered. Apparently jugs and ewers were the most abundant type of vessel found in the workshop area (Gilbert pers. com.). This is notable because undoubtedly the workshop would have been a hot place to work. The jugs probably provided liquid refreshments for the craftsmen.

An archaeobotanical study of plant remains from MGK 4 was done by S. Boardman. She identified wheat, barley, vivieae (pulse), cucumber/melon, watermelon, grape, almond/peach, thick walled nutshell, cotton, prosopis (cat's claw), alhagi (camel thorn) and small seeded legumes (Herrmann *et al.*, 1997, 29-31). The craftsmen may have eaten the nuts and fruits during work; however, the use of some of the plants, possibly the rinds, in the production of crucible steel is also a possibility (see below).

Types of Material Remains

All the excavated remains, up to and including those from the 1996 excavation which were not identified as "domestic" items (e.g. ceramics, gaming pieces) or coins, were visually examined by the author for initial categorisation. Their "typical" and "atypical" physical characteristics were recorded for comparison with known processes from other locations. The majority of remains were catalogued, weighed and measured either at Merv or in London (Appendix B). Unfortunately, during surface clearing of the crucible pit in 1996, finds were not collected, save for sieving two buckets of dirt, and a few finds recovered from the spoil heap. Therefore, some evidence may be missing and has now been removed from its primary context.

The pit was not a single pit but a series of inter-cutting pits. The pits were densely packed with debris deposited in stratified layers. During the excavation in 1994 and 1996 a trench was cut through the pit. Roughly 20% of the pit was excavated. The shape of the pit was roughly half and ellipsoid with the radii measuring 3.5 m, 3.5 m, and 0.5 m, respectively. The volume of the crucible pit was estimated by calculating the volume of the ellipsoid, using the standard calculation $4/3\pi\ r_1\ r_2\ r_3$, where r = the radius, ($4/3\pi$ 3.5 x 3.5 x 0.5 = 25.65632) and then dividing it by half resulting in a total volume of 12,282 cubic meters. The volume in cubic meters was converted into the volume in litres resulting in 12,282 l of material in the pit including industrial remains, domestic debris, ash and sand.

All the remains collected during the survey and the 1993 surface scrape were exported thus providing the bulk of random samples. During the excavations, only crucible fragments that were relatively large or contained particular features, such as a slag fin, luting or an abundance of rusty encrustations on the interior, were selected for export.

After visually examining all excavated industrial debris and choosing those for export, a further selection was made for laboratory analysis. A summary of the recorded excavated and exported industrial related remains is given in Table 2.

Table 2: Summary of Types of Remains Exported*

Type of Material remains	Number Recorded	Number Exported	Estimated Average size in cm
Fragments of crucible lids	~150	30	5 diameter
Fragments of crucible walls	~ 500	70	6 height
Fragments of crucible bases with pads	~130	35	6
Pads alone	~10	2	4
Green glassy slag	~150	75	1
Corroded iron/steel pieces	~100	All	1
Furnace fragments	~100	20	10
Unidentified slag/ore	~ 60	All	5
Copper alloy debris	~ 85	All	0.5
Glass fragments	~ 20	All	2
Rock fragments	~ 5	All	4
Vitrified mud	~100	2	20

* This table summarises the main types of industrial debris excavated at MGK 4, including some surface finds from the adjacent area (unidentified slag and copper debris). It must be stressed that the numbers represent fragments, many less than 0.5cm at the largest point, particularly the copper - alloy debris. The sole purpose of this table is to give the reader an impression of the total number of fragments recorded, their average size, and the relative number exported for in depth laboratory examination. As the entire workshop area was not excavated, the numbers do not represent all the remains from the workshop, nor have all the excavated fragments been recorded, weighted and measured, therefore the information cannot be used for statistical purposes.

Crucible Fragments

All excavated crucible fragments were visually examined on site. No complete crucibles were unearthed. Based on their visual appearance, the fragments were divided into lids, walls, and bases. The examination concluded that the fragments were from a single type of lidded crucible, which sat on a (so-called) pad.

All lid fragments are from flat ceramic disks *c.* 8 cm in diameter with a thickness ranging from 0.5 to 1 cm and they have a central hole 1 cm in diameter, slightly raised proud on one side (Figures 6). There are impressions of parallel lines, on the underside of the lid (Figure 7). Around the exterior circumference there remains evidence of an applied ring of clay, luting, which attached the lid to the crucible wall (Figure 8).

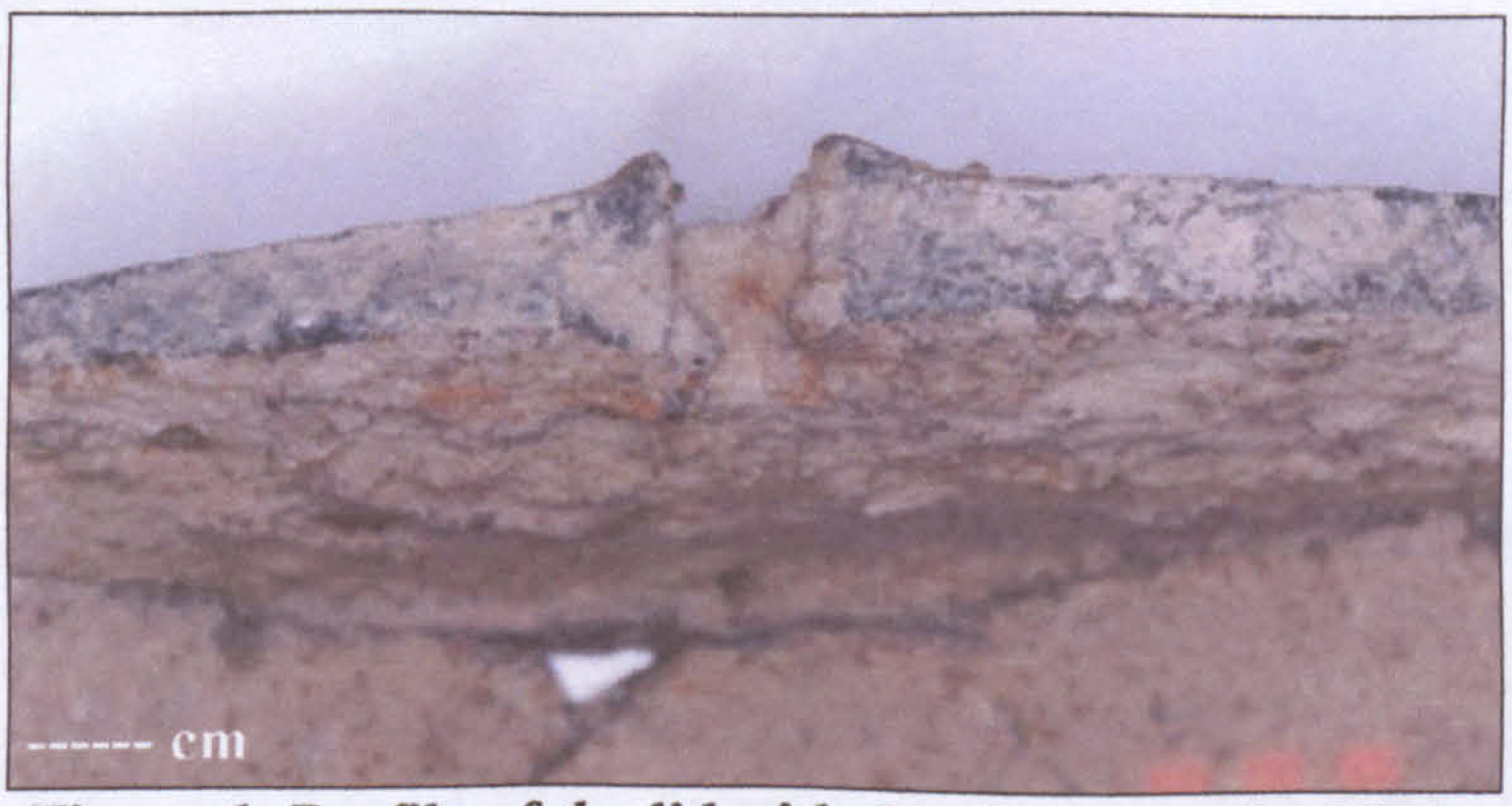


Figure 6: Profile of the lid with detail of the raised hole.

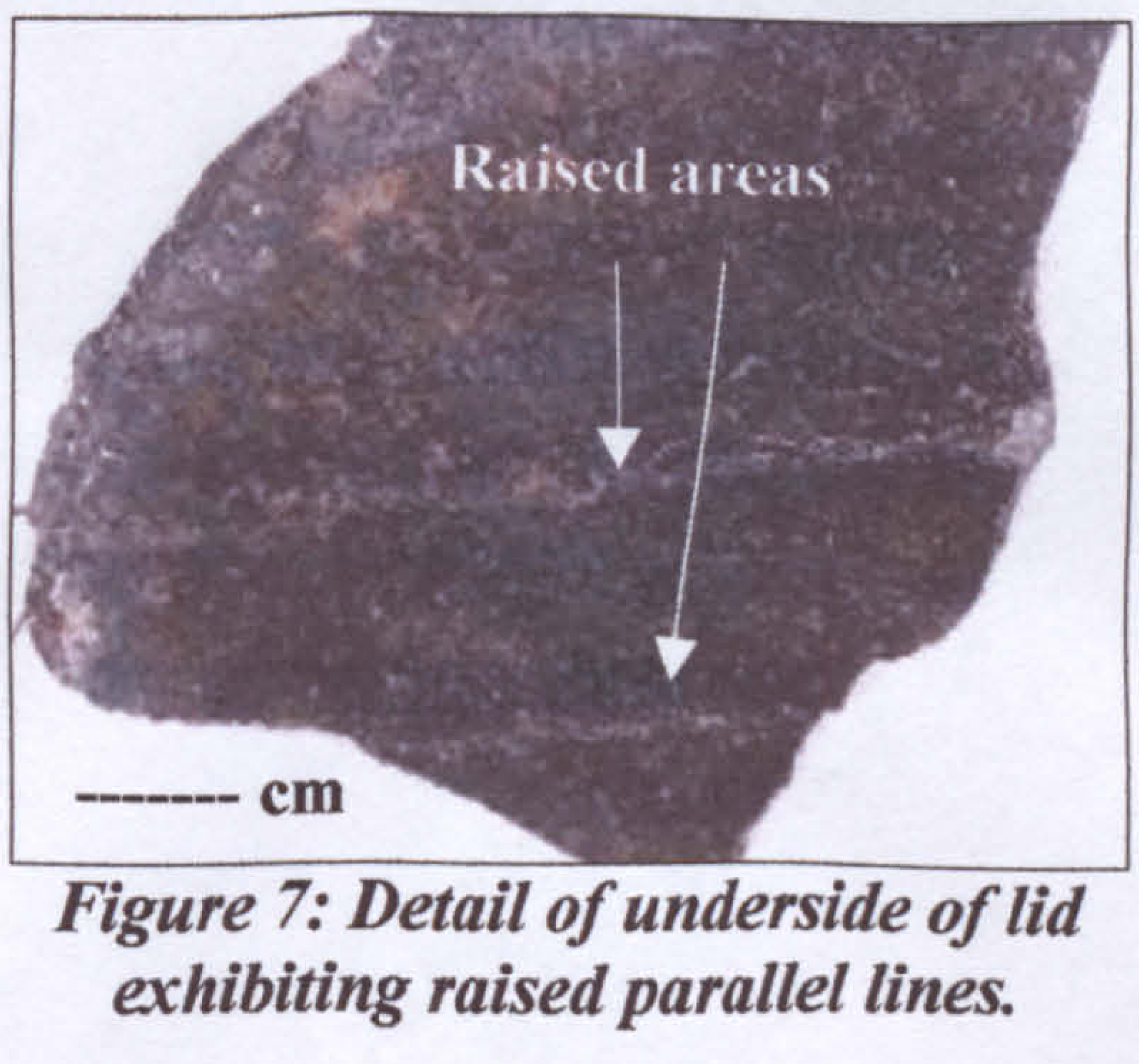


Figure 7: Detail of underside of lid exhibiting raised parallel lines.

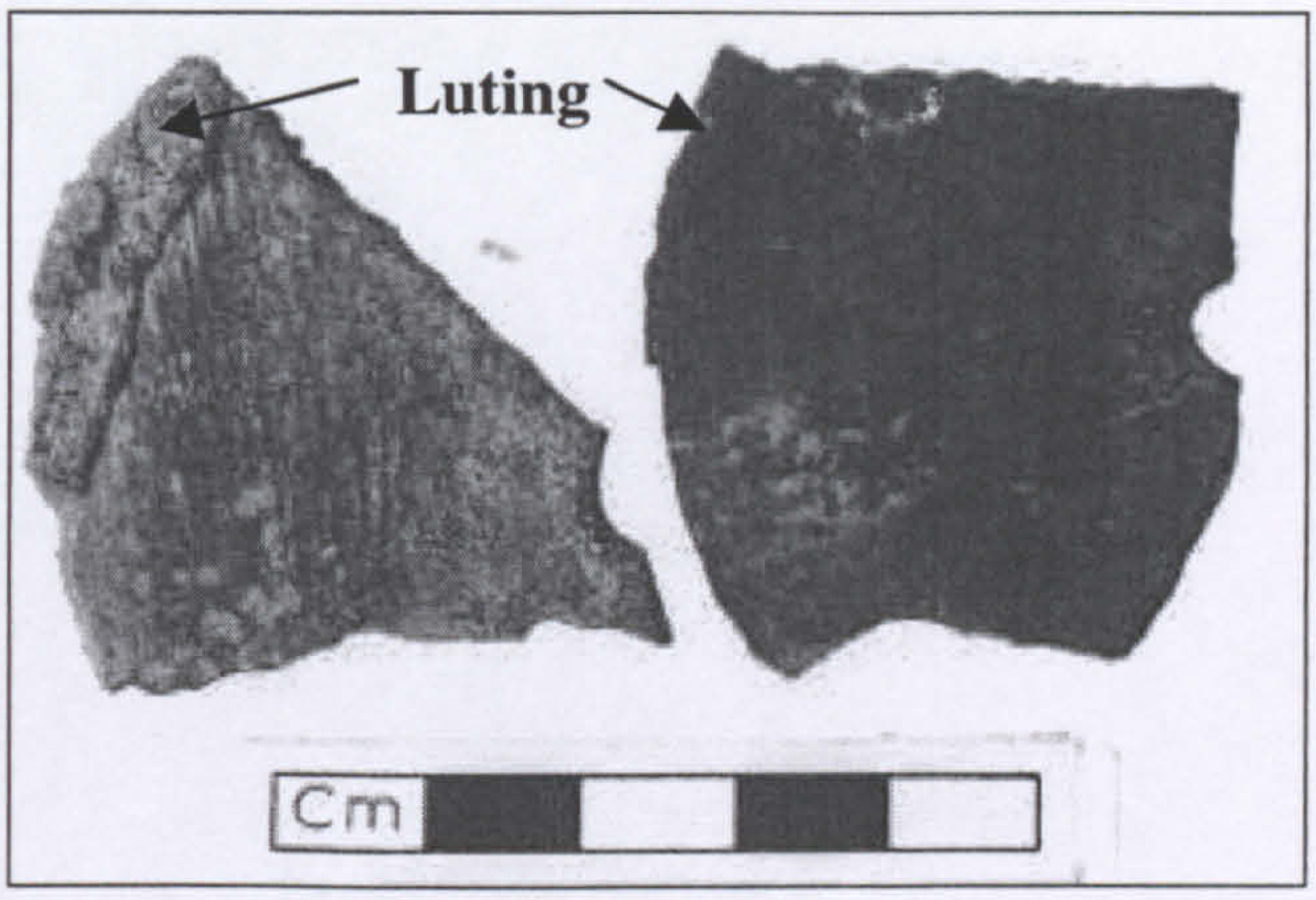


Figure 8: Two lid fragments with remains of luting.

The crucible wall became thinner and darker the closer it was to the lid. The colour and thickness changes from white and *c.* 1 cm in thickness, at the lower part of the wall near the base, to dark grey and *c.* 0.5 cm, at the upper part of the crucible where it meets the lid. Another feature on the exterior side of all the wall and base fragments was a shiny black glaze, occasionally with reddish lines and undulating (wavy) pattern. The black glaze is thinner, *c.* 0.1 cm on the upper parts of the wall, and thicker, *c.* 0.5 cm towards the pad. These features are assumed to change uniformly along the height of the crucible.

There are rust coloured encrustations on the underside of some lids, and on the interior side of the upper walls of the crucible (Figure 9). These were identified as partially corroded steel prills (see *Iron and Steel* below). Below these rusty encrustations, towards the base, is a glassy green ring identified as slag (see *Slag* below). The location of the glassy green fin averages around 8 - 10 cm high from the base measured at the inside of the crucible.

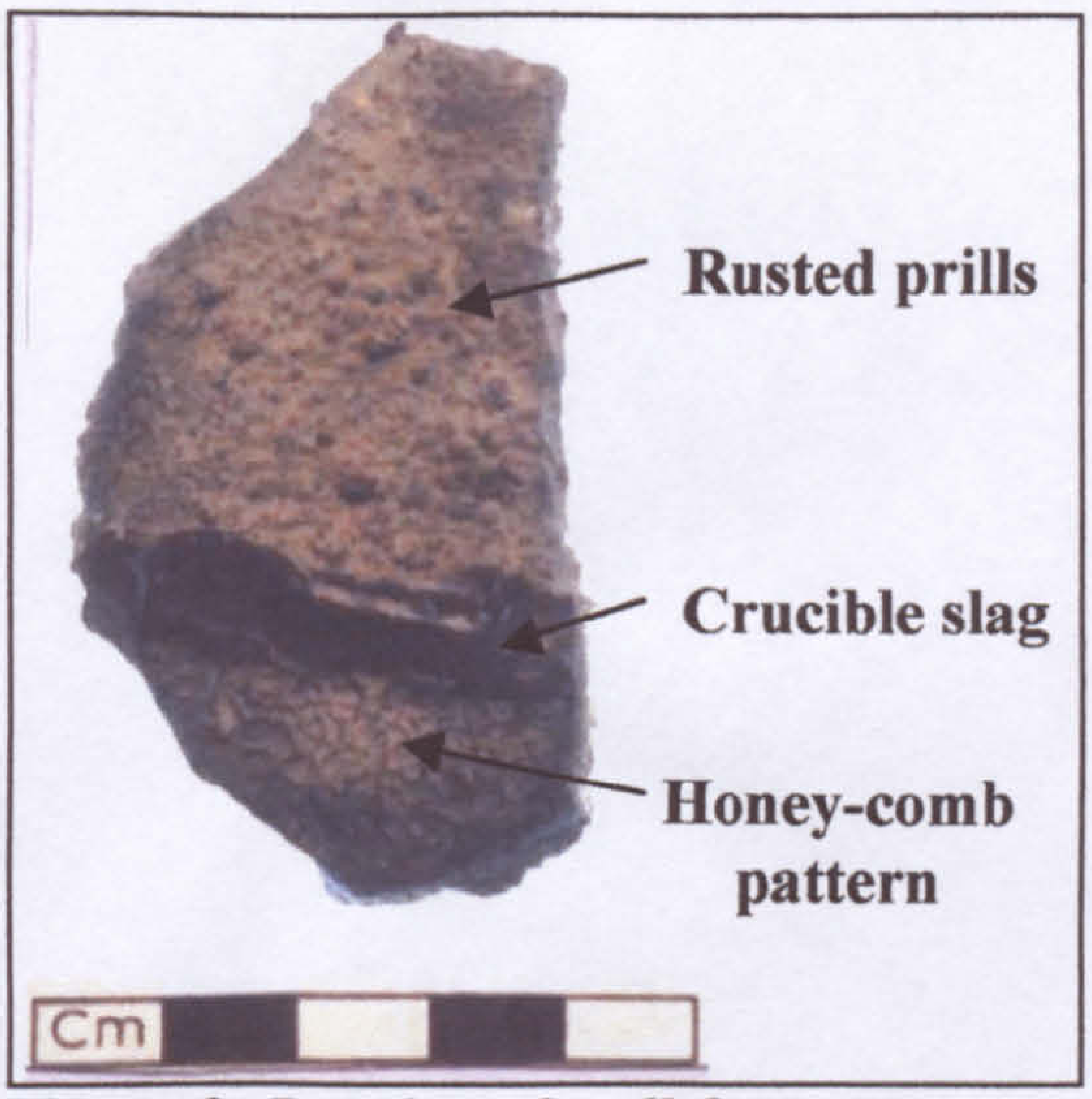


Figure 9: Interior of wall fragment.

The internal profile of the lower part of the wall to the base, below the glassy green slag, is hemispherical with a thin layer of a dark green vitreous slag, which sometimes has a honey-combed pattern or is comparatively smooth. The interior diameter of the bases varies from *c.* 6 cm to *c.* 6.5 cm, although the external diameter is consistently *c.* 8 cm (Figures 10, 11 and 12). The crucible bases have an external bottom profile that is either flat or slightly arched, probably due to being placed on to the pad while still in a comparatively malleable state (Figure 13). The base of the crucible has a disk shaped attachment, a (so-called) pad, made of a different ceramic fabric (Figure 14). The diameter of the pad is *c.* 8 cm and it has a thickness of typically between 1 and 2 cm. Pieces of broken crucibles, *c.* 1 cm^2 and 0.5 cm thick are attached to the pad's perimeter by a black glaze. These are labelled "refractory mass" and are interpreted as part of the furnace floor (see *Furnaces* below).

Figures 10 and 11: Two crucible bases with pads attached.

Figure 12: Profile of crucible base.

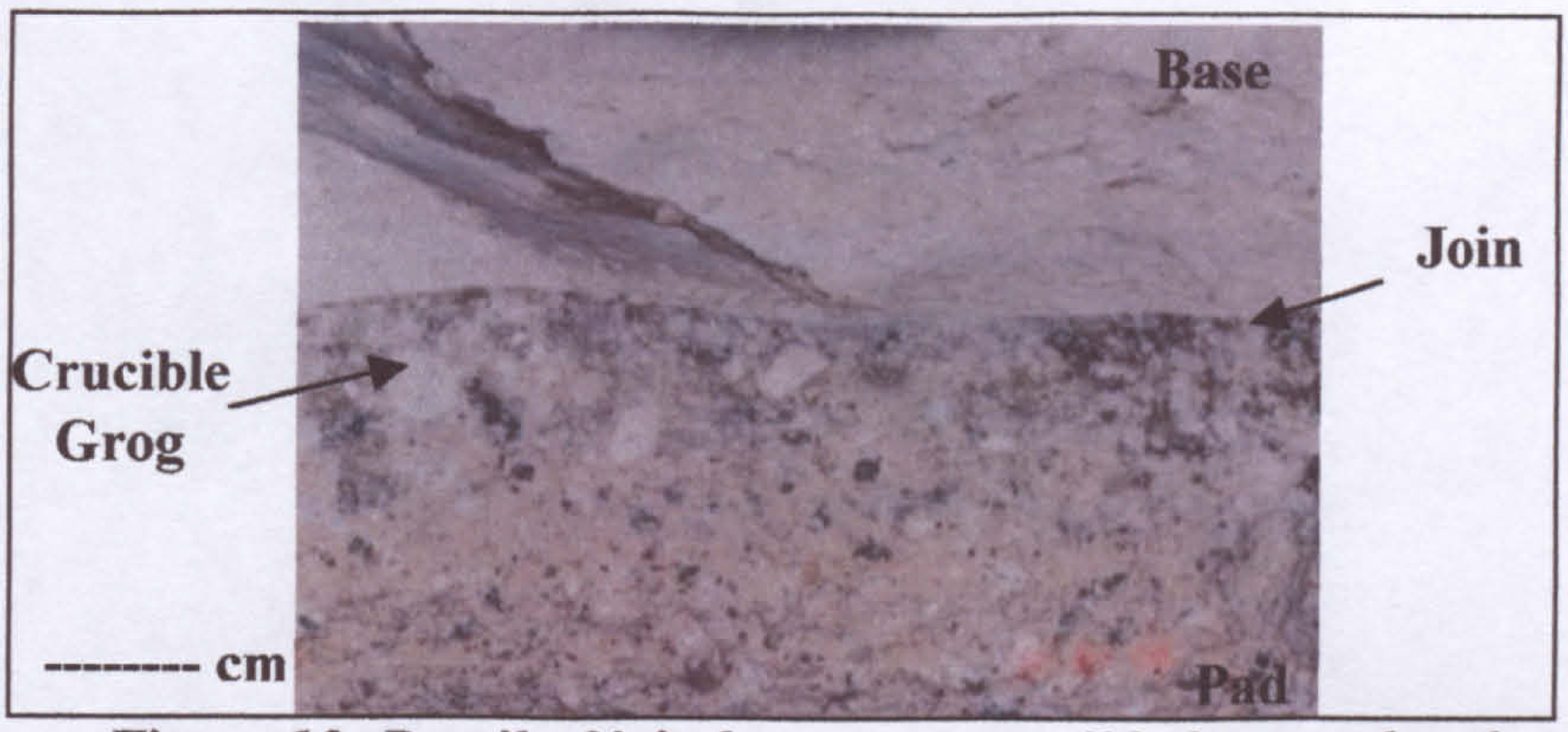


Figure 13: Detail of join between a crucible base and pad.

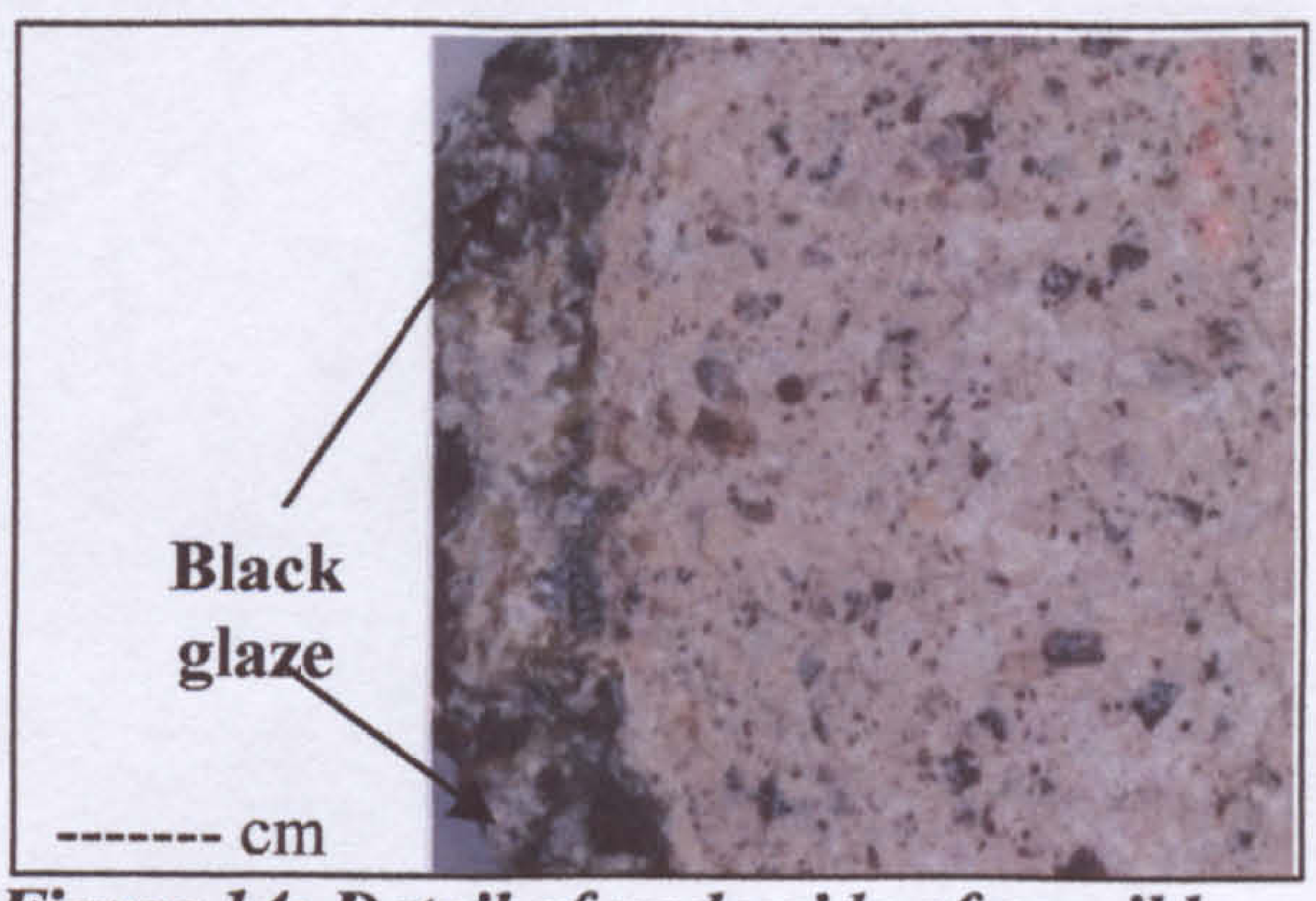


Figure 14: Detail of underside of crucible pad with attached black glaze.

By observing the rate at which the wall features apparently changed from the base to the lid, the height of the crucibles is estimated at between 18 and 20 cm. The lid, wall and base fragments all indicate that the shape of the crucible was a flat-bottomed cylinder with an external diameter of *c.* 8 cm and an average internal diameter of about 7 cm at the top and 6 cm at the bottom (Figure 15).

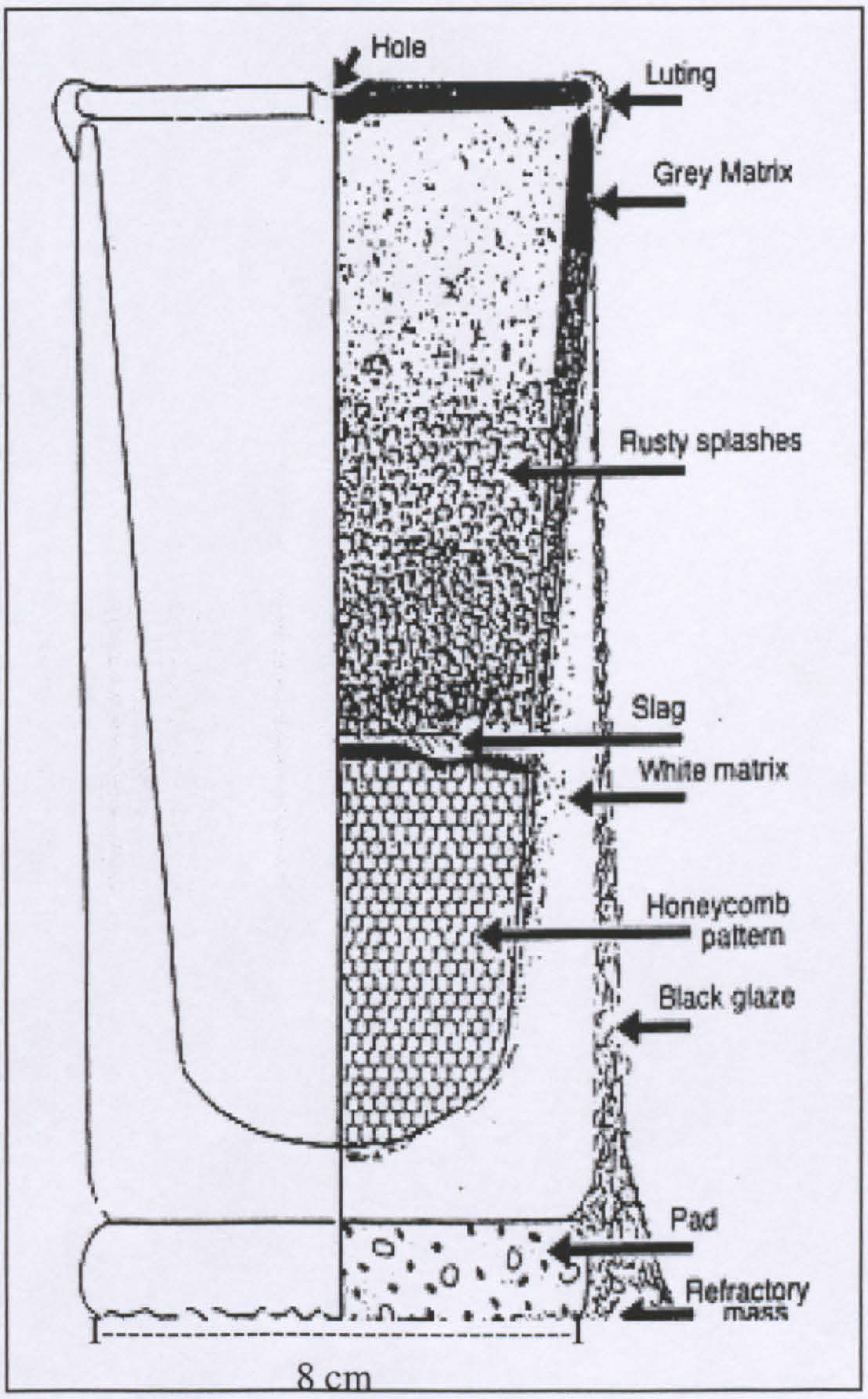


Figure 15: Reconstruction of Crucible.

In London, reflected and transmitted light microscopy together with x-ray diffraction and electron microscopy were used to determine additional characteristics of the crucible fragments. Thirteen samples were selected for petrographic analysis: 3 lids, 4 walls, 4 bases, and 2 pad fragments. The samples were chosen because they appeared to be representative of the crucible assemblage. At least one sample, which appeared high fired and another that appeared low fired, was taken from each part of the crucible (e.g. one high fired lid and one low fired lid sample). The degree of firing was determined by observing the apparent degree of vitrification/glassiness of the cross-section. Six samples were analysed by x-ray diffraction: two lids, two walls and two bases, each representing a higher fired and a lower fired sample. The results of the petrographic and x-ray diffraction analyses were used to determine the minerals present with the aim of identifying the materials used for the crucibles construction, and to suggest firing temperatures.

Petrographic analysis, backscattered images and elemental analysis indicated that the crucibles were tempered with quartz and crucible grog. Quartz was identified as a colourless crystal that exhibited straight extinction in polarized light (Figure 16). Visual estimation of the percentage of quartz in the total crucible volume is between 0-15%. Most of the quartz inclusions are 0.05 mm to 5 mm in length and heavily cracked (Figure 17), presumably from the thermal shock upon heating and cooling (Rice, 1987, 96). Some of the quartz inclusions have rounded edges probably due to alteration of the quartz caused by the high firing temperature and contact with fluxing agents in thc clay matrix. Most, however, are angular with low spherocity most likely caused by crushing the quartz before adding it to the clay as temper. Overall the quartz appears to have a preferred orientation, aligning roughly parallel to the crucible wall. The quartz inclusions that are less than 1 mm in diameter, and, because of their small size, are assumed here to be from the original clay source. However, the small size of the fragments suggests that they may have been introduced as powder from the crushing process along with the deliberately added quartz.

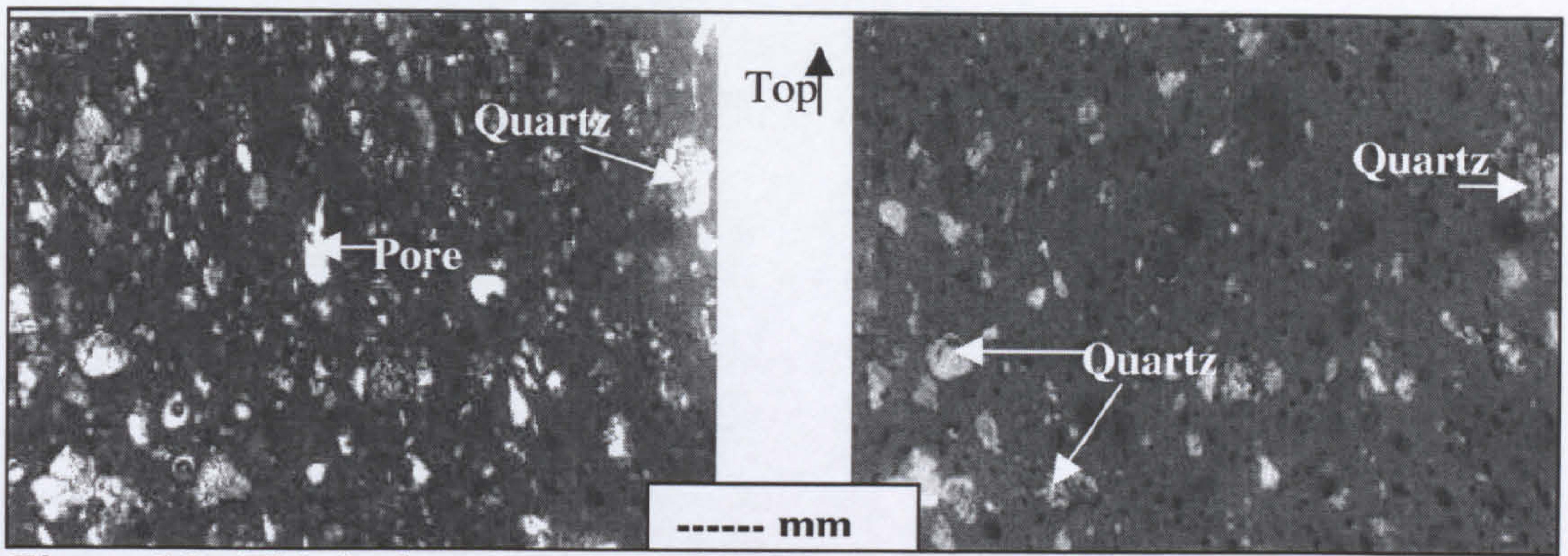


Figure 16: This is the same area of thin section of a crucible base photographed under plane polarized (left) and crossed polarized light (right).

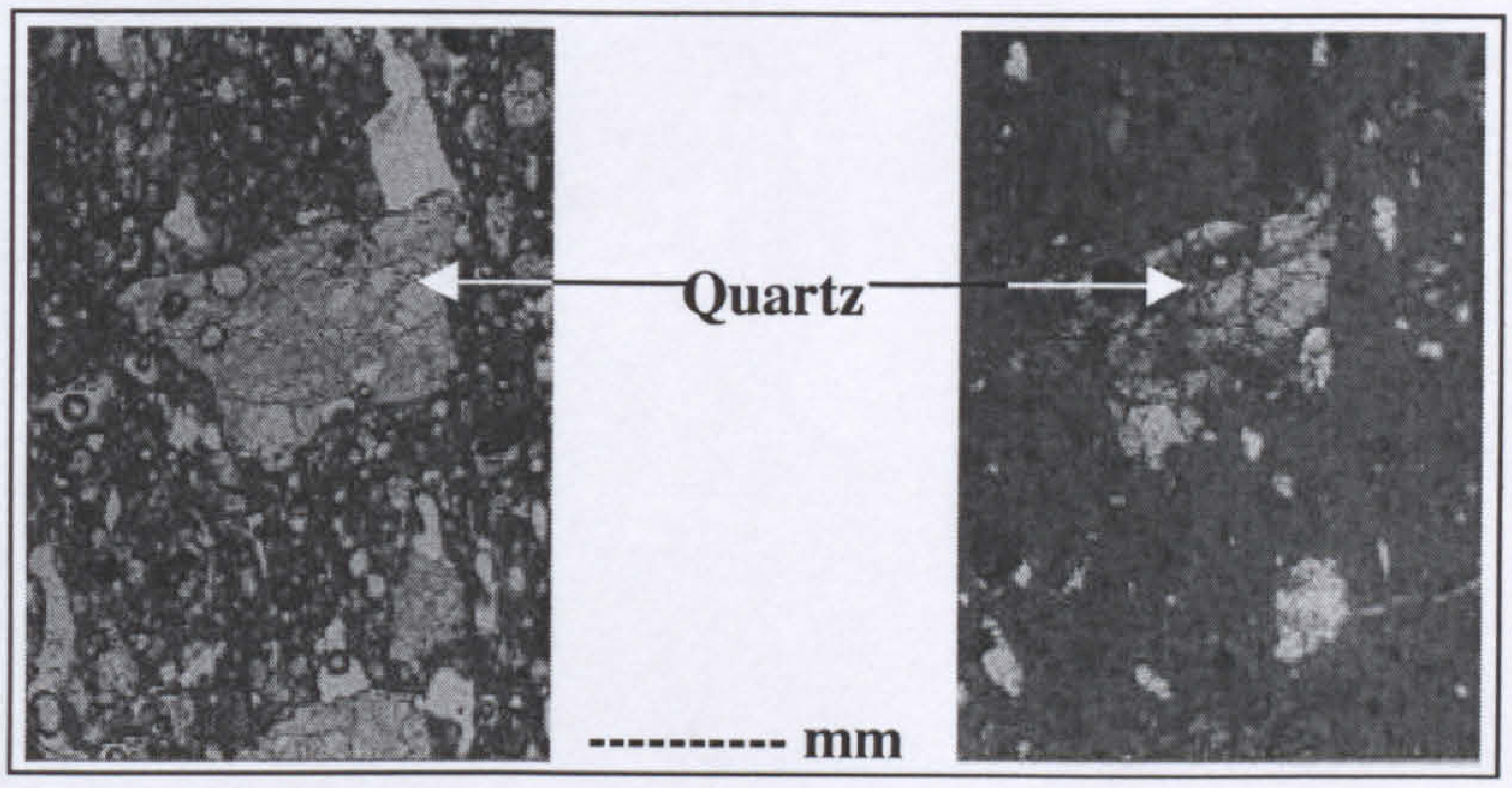


Figure 17: Detail of a cracked quartz inclusion from a thin section from a wall fragment, and photographed under polarized (left) and crossed polarized light (right).

The second type of inclusion was identified as crucible grog because it appears matte and white in hand section and under reflected light, and opaque in transmitted light. In addition, its composition, as determined by SEM/EDS, was the same as the crucible fabric. These inclusions were easily observed in the lids and the top of the crucible because the white grog visually contrasts with the dark grey matrix (Figure 18). The grog was not easily observed in the white higher fired areas because the edges have melted into the crucible matrix and are the same colour, however the grog can be observed in thin section as small (*c.* 0.5 cm) localised areas with different optical properties to the surrounding ceramic matrix and the quartz inclusions in the grog have a different preferred orientation to the quartz inclusion in the rest of the crucible fabric. It is estimated that grog composes between *c.* 0-15% of the total volume of the crucible fabric.

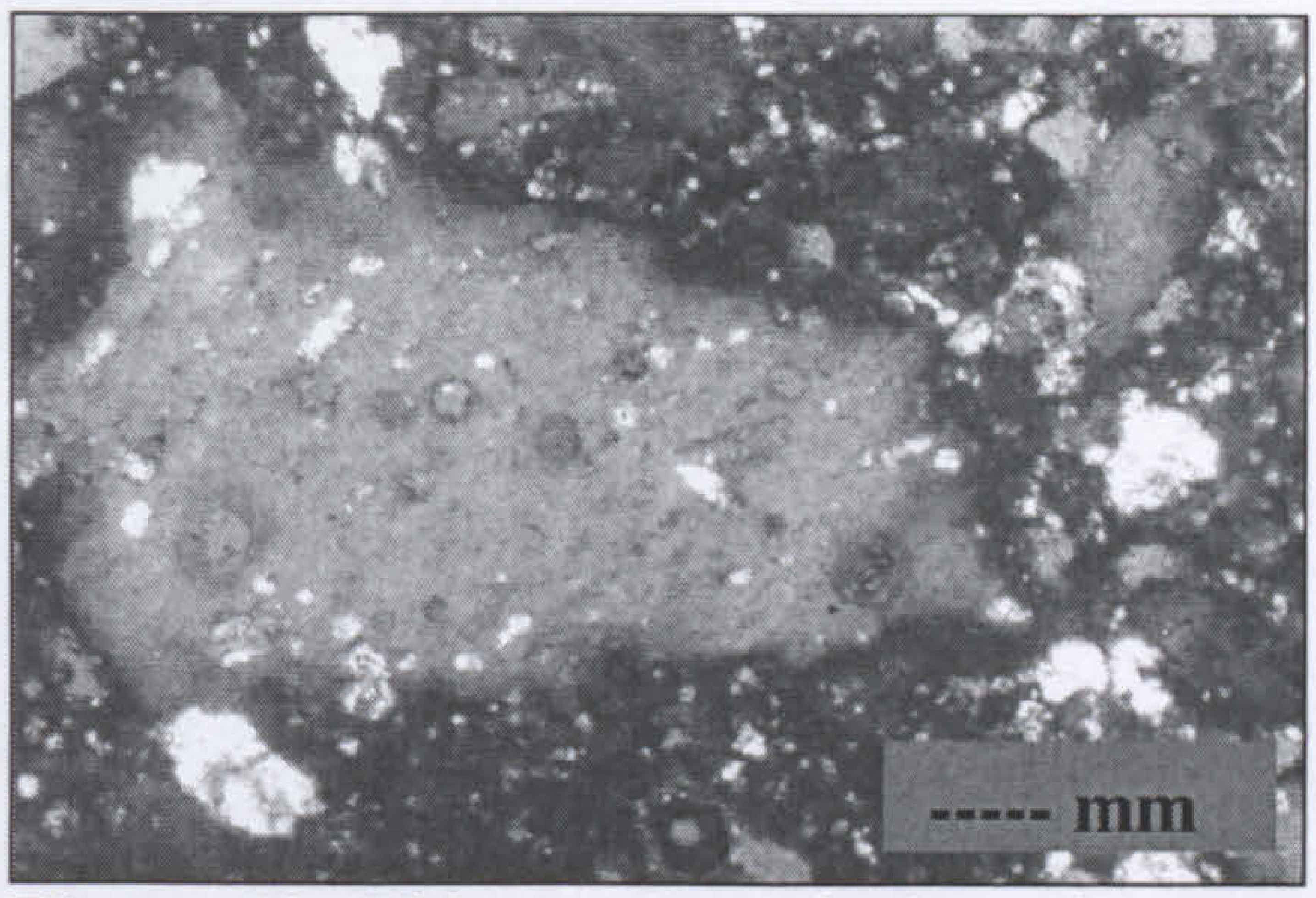


Figure 18: Thin section of a base fragment illustrating crucible grog

The total percentage of inclusions in the composition of the crucible fabric differed between samples, from virtually absent to being present in quantities up to *c.* 15% of the total volume (quartz + grog = 5%-15%). The pads also contain quartz inclusions and crucible grog. The grog composes approximately 20% of the pads fabric and is less well sorted than grog in the crucible, indicated by the presence of pieces of black glaze, the same size as the crucible grog (see Figures 13 and 14 above).

The varying quantity of inclusions, their low spherocity, and the use of grog, indicate that many of inclusions were deliberately added temper. This difference in quantity may be due to a change in the supply of the raw material, possibly because of a change in trade patterns, restricted access to the source, a raise in the price of clay, or reflecting a different potter, to name just a few possibilities. One method, which could have been employed to help solve this question, would have been to excavate and study separately each inter-cutting pit to determine their depositional sequence. One would expect to find that crucibles from an early phase would have had less temper, when the clay supply was presumably plentiful, than those from a later phase when the clay was scarce. Alternatively, the knowledge of tempering may have been introduced to the potter during the lifetime of the workshop or it may indicate a change of potters. In the absence of such finely stratified data, the reason for the difference in quantity of inclusions remains undetermined.

In addition to acting as filler, the quartz and grog temper would have served additional functions. Temper can improve workability and green strength (unfired state), improve thermal properties, assist in drying, and hamper cracking on firing and cooling (Kilikoglou *et al.,* 1998, 261; Rice, 1987, 408). Therefore, the quartz and grog in the crucible would have:

1) Reduced the plasticity of the clay thus assisting shaping.
2) Improved physical support of the unfired crucible by retarding slumping by adding non-plastic components to the clay, an important feature considering that the crucible needed to hold the crucible charge.
3) Reduced shrinkage upon drying by providing physical support.
4) Hindered the growth of cracks, caused by shrinkage or thermal shock by dispersing the cracks energy around the circumference of the temper.
5) The grog would have been particularly effective in reducing thermal stress because it would have a thermal coefficient similar to the clay (Rice, 1987, 229).

All the lids have a dark grey matrix with white and occasionally yellowish inclusions, and pores that vary in size from 1 mm to 5 mm. Some lid fragments contain minute organic fibres (Figure 19). Their small size and low frequency suggests that they arrived as contamination and were not deliberately added to the clay as temper, however the possibility cannot be completely ruled out. The lids uniform diameter but varying thickness, suggests that they were rolled out on a flat surface and then cut out with a form (akin to a modern biscuit cutter). The parallel line impressions may have been caused by the rolling out of a slab of clay onto a wooden or woven surface where they may have picked up the minute fibres.

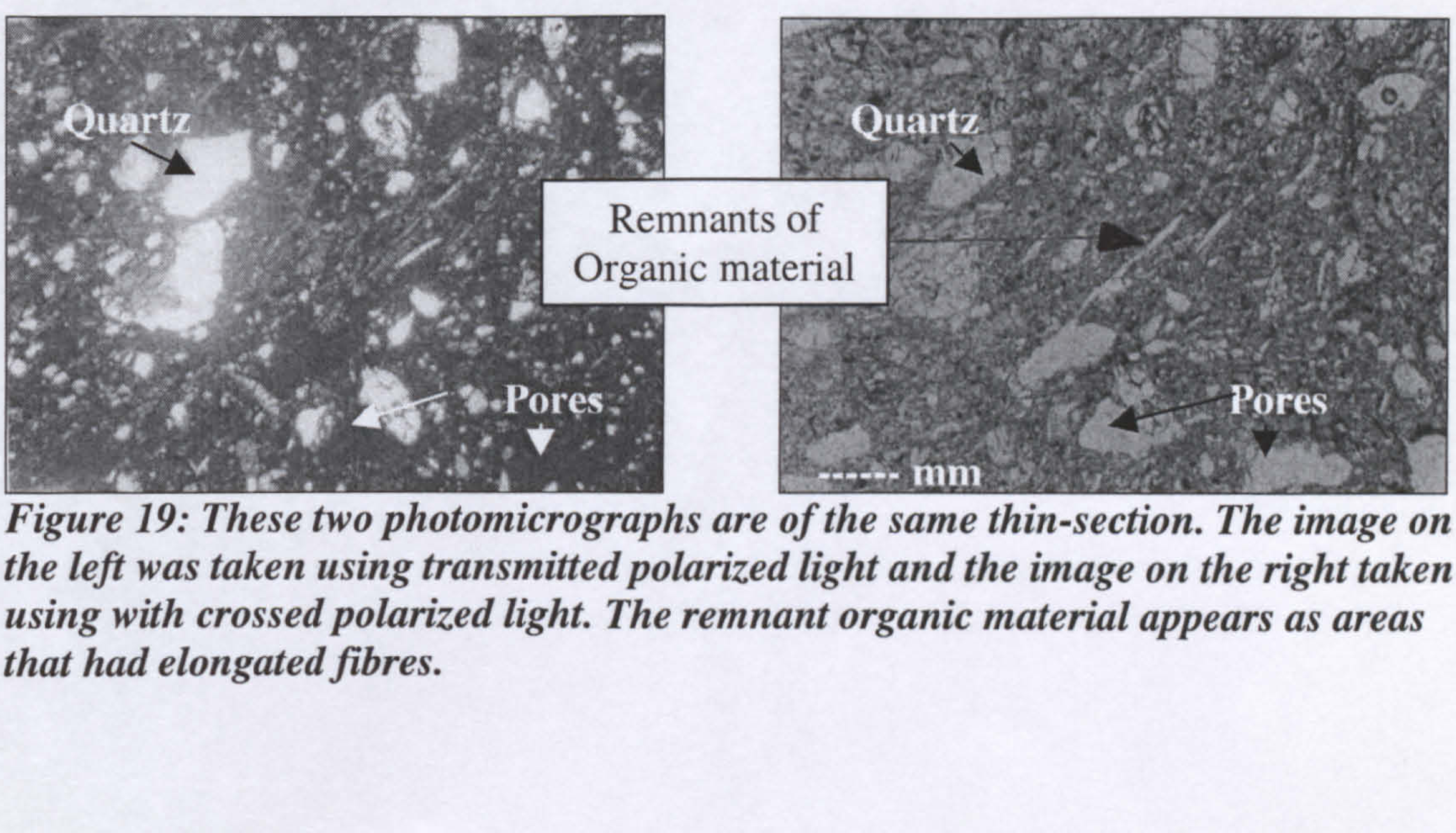


Figure 19: These two photomicrographs are of the same thin-section. The image on the left was taken using transmitted polarized light and the image on the right taken using with crossed polarized light. The remnant organic material appears as areas that had elongated fibres.

The body of the crucible was made by a different method. It was thrown on some type of rotating device. The uniformity of wall thickness around the circumference, the thinning of the bases and walls towards the top (see Figures 11 and 12 above), spiral fracturing (see Figure 13 above), and the preferred orientation of inclusions (see Figures 16 and 17) are all characteristic of wheel thrown vessels (Rye, 1981, 75-80).

Some bases are too thin to have been made in such a way during throwing without tearing the base when removing it from the wheel, suggesting that the base was trimmed of excess clay. The trimming would have performed two functions. Firstly, the excess clay could be used to make another crucible. Secondly if the base was too thick it may have cracked and therefore failed, however, in the crucible illustrate in figure 10 (above), the trimming was extreme and the crucible would have failed if the pad were not applied. Trimming, along with the use of grog and quartz temper and the use of a pad, suggests that the craftsmen were concerned about conserving clay.

Bloating pores are also present in the crucible fabric. Porosity is not a deliberate addition to the clay matrix but "is basically created by release of gases (mainly CO_2) or evaporation of water during firing as well as any cracks that may develop during drying and firing" (Kilikoglou *et al.*, 1998, 269). The pores are fairly round and of the closed variety (Rice, 1987, 350). The larger pores are *c.* 1 mm in length, the smaller are 0.1 mm to 0.2 mm. The pores near the exterior occur less frequently but they are larger. Near the interior more pores occur but they are smaller (Figure 20). This was to be expected because the heat source was outside the crucible therefore the exterior would have reached a higher temperature for a longer period of time, thus allowing pores to merge in the vitrified areas. Porosity would have reduced thermal stresses by stopping cracks much in the same way as the inclusions.

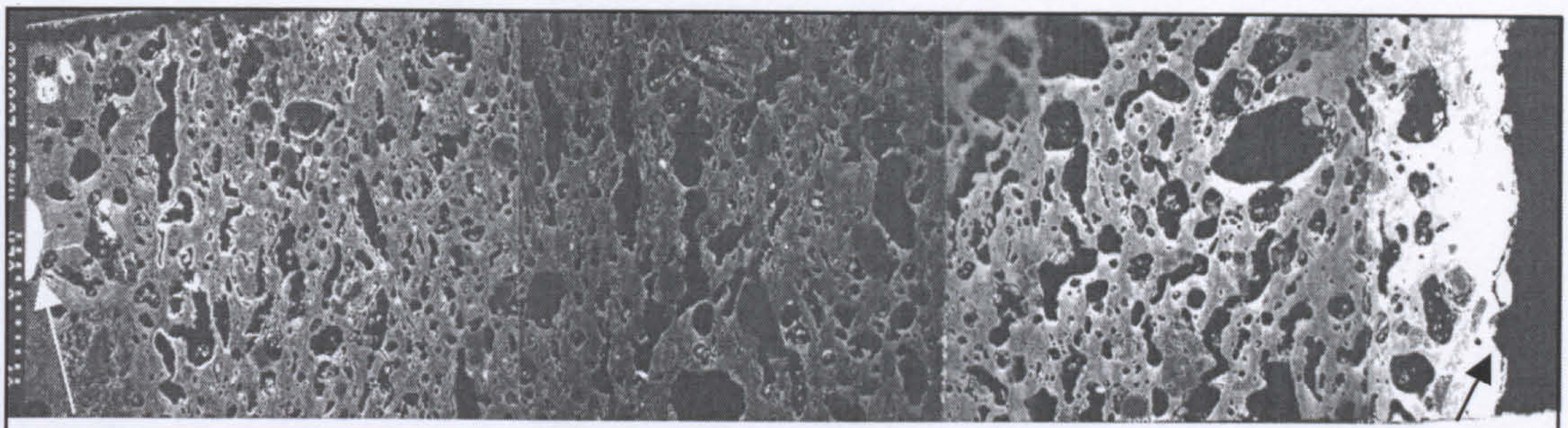


Figure 20: This is a backscattered image of a cross section through a crucible wall illustrating the larger pores near the exterior glaze (right) and smaller ones towards the interior (left).

Differences in the degree of vitrification in the crucible matrix were observed around the circumference of the crucible and along the height. The degree of firing was determined by visually observing the ratio of crystalline to glassy phases in the crucible matrix. The ratio of crystalline to glassy phases is more pronounced in some sections than in others, indicating differences in firing temperature or time and suggests steep thermal gradients between different parts of the crucible. This would have produced a high degree of thermal stress. Thermal stress would be the primary cause of crucible failure and therefore be a highly important consideration for the craftsmen.

Within the glassy vitrified areas, pinpoint size crystals have begun to form. These were identified by x-ray diffraction as mullite[1] (Appendix C). All analysed samples contained mullite and all but one contained cristobalite. Some of this quartz may have converted to cristobalite. Cristobalite is a high temperature form of SiO_2, and is sometimes a product formed during the change from clay to mullite (Rice, 1987, 95). The observations in backscattered electron images indicated that the amount of mullite increased in the higher fired pieces. Mullite is resistant to corrosion and heat and is often used in refractory materials. It is particularly resistant to acid metal slags (David and Pask, 1971). Quartz transforms to cristobalite and stabilizes at 1470^{O}C (Rice, 1987, 95). However, cristobalite forming out of free SiO during the transition to mullite occurs at much lower temperatures, 1050^{O}C – 1100^{O}C. Therefore, the mullite determined that the minimum temperature the crucibles reached was 1050^{O} C.

[1] Mullite is an aluminium silicate ($Al_6Si_2O_{13}$).

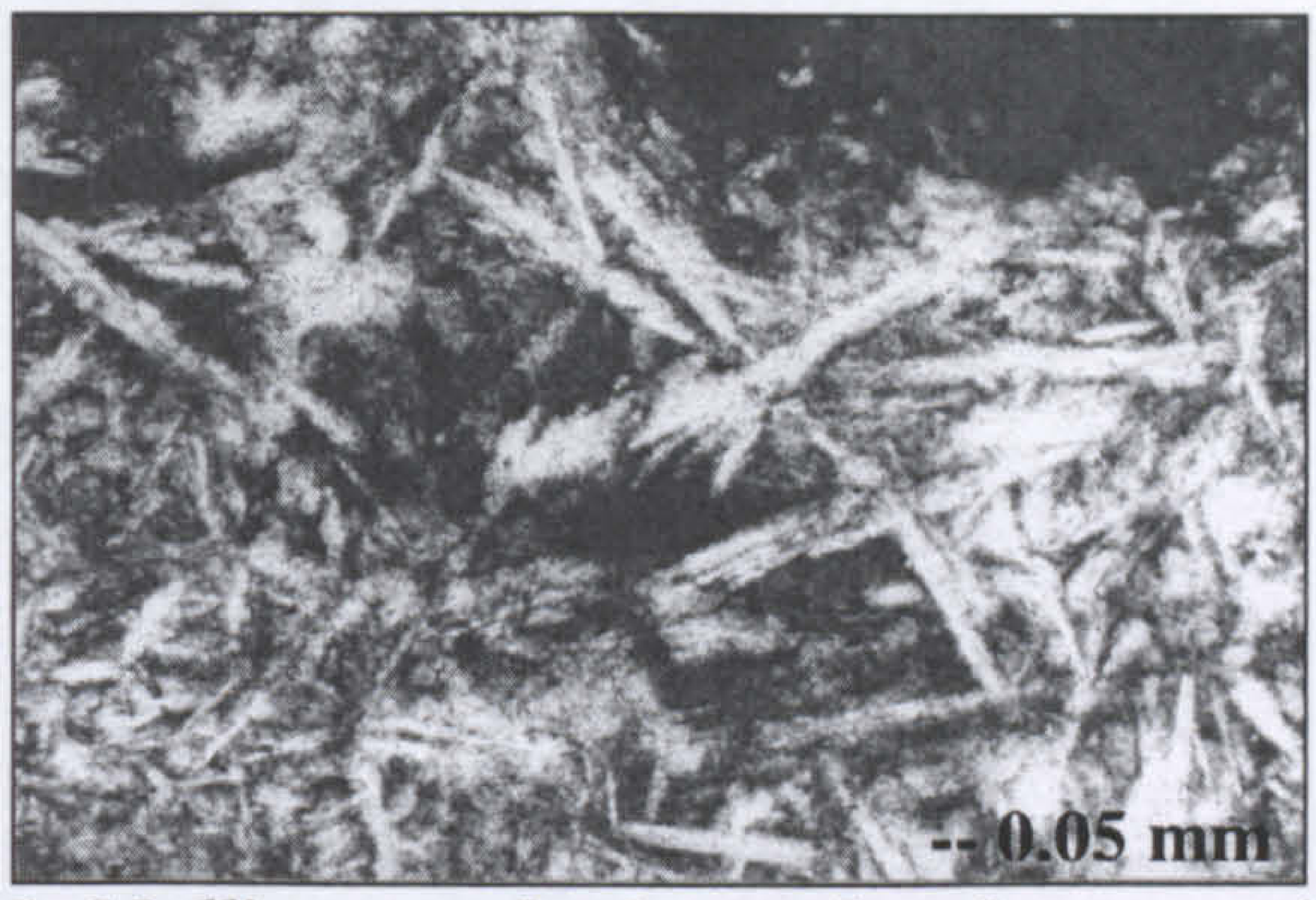


Figure 21: Mullite crystals observed under transmitted light.

The crucibles' inclusions, matrix and exterior black glaze were initially examined using SEM/EDS. A selection of thin and polished sections were analysed using 10KV because the machine was calibrated for geological samples using this voltage. More detailed examination was performed using EPMA/WDS on polished samples. The applications, analysis and problems of using EPMA/WDS to study ceramics can be found in Ruddlesden (1967, 587- 598) and Ruddlesden and Airey (1967, 599-629). Three points were analysed on each phase in question and averaged together to propose the phase's average composition. Initially twelve wall samples were analysed to determine the composition and similarity of the ceramic matrix in different samples. An area approximately 900 μm^2 was analysed using 20KV. The fairly large area resulted in total oxides around 85%. This low total was assumed to be primarily due to porosity. The analyses did, however, indicate that the wall samples were all composed of a similar matrix, implying they were all made using the same type of clay.

In order to improve the totals and compare the matrix composition between lid, wall and base fragments, ten more samples (3 lids, 3 bases and 1 wall) were analysed using the same method but over a smaller, *c.* 100 μm^2 area, also using 20KV (Appendix D). Totals were higher in the higher fired bases than the walls and lids by about 1%, presumably because the higher ratio of glass to crystallised areas in the matrix resulted in less microporosity. However, the glassy areas may be somewhat unrepresentative of the matrix's elemental composition, containing a high percent of fluxing agents. The normalised results of the 900 μm^2 area and the 100 μm^2 area are consistent with each other and the range in the percentage of elements within each sample and analysis is characteristic of ceramics (Rice, 1987, 31-53) in that they are primarily composed of silica (65%) and alumina (24%).

The elemental composition of the crucible fragments clay matrix was determined by electron probe microanalysis. They were found to be composed primarily of SiO_2 (*c.* 65%) and Al_2O_3 (*c.* 24%) with small amounts of K_2O (*c.* 4%) and CaO (*c.* 0.5%). All fragments appear to be made of the same clay (Table 3).

Table 3: Elemental Composition of the Crucibles (Averages)

	SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	TiO_2	Total
Lids	63%	24%	4.7%	0.8%	0.3%	0.3%	0.7%	0.5%	95%
Walls	67%	22%	4.0%	0.3%	0.2%	0.1%	1.2%	0.5%	95%
Bases	65%	25%	4.5%	0.4%	0.1%	0.3%	1.3%	0.4%	97%
Crucible	**65%**	**24%**	**4.4%**	**0.5%**	**0.2%**	**0.2%**	**1.1%**	**0.4%**	**96%**
Pad	59%	24%	2.7%	7.9%	0.2%	0.7%	1.1%	0.5%	96%
Luting	65%	20%	6.4%	0.5%	0.4%	0.2%	0.4%	0.1%	93%
BlackGlaze	52%	20%	4.5%	13%	0.31%	1.5%	1.2%	0.4%	94%

See Appendix D for full results. Elements analysed for, but were either not present or present in quantities below the detection limit were Ba, P, Mn, V, S, Ni, Cu and Cl.

The ratio of silica to alumina is *c.* 3:1. The small percentage of colouring elements, particularly iron, accounts for the white firing colour of the base. The low percentage of fluxing agents compared to ordinary clay, (e.g. FeO, K_2O, CaO, Na_2O) and the comparatively high percentage of alumina (*c.* 24%) accounts for the clay's refractory nature. The clay fires to a white colour and is comparatively refractory therefore it can be considered to be kaolin-like in nature.

The calcium content varies significantly between samples from 0.3 - 0.8%. This is interpreted as the result of the choice of areas analysed and not representative of the matrix as a whole. In one base sample, glassy areas were analysed. This may represent an area that had an inclusion with a high calcium content that locally fluxed the matrix. One crystalline phase present in the glassy base, had a high calcium content (*c.* 15%). The presence of calcium would have been undesirable because it would have acted as a flux therefore the calcium rich inclusions were probably not deliberately added temper.

Slightly more sodium is present in the lids than in the body or base fragments and the visual examination revealed that some lids exhibit a thin layer of glaze on the underside of the lid. This is interpreted as a sodium glaze resulting from the vaporisation of sodium from the crucible charge (see *Slag* below). The glaze on the underside of one lid sample (#78) was analysed and did have more sodium (0.52%) but also more calcium (15%) than the ceramic matrix. The sodium and calcium acted as a flux and created a reaction similar to a salt or ash glaze (Rice, 1987, 100). The possibility that the glaze is indeed an ash glaze formed by the crucible charge ingredients cannot be ruled out (see proposed reconstruction below). The titanium rich inclusion and this presence of *c.* 0.5% titanium in the crucible fragments suggests that it is from the original clay deposit.

The composition of the pads is different from the crucible clay and is much more inhomogeneous, with areas of complete vitrification. The matrix at the bottom of the pads is lower fired and slightly beige in colour with a friable texture but becomes whiter, more solid and glassy towards the top, where the pad meets the base (see Figure 13 above). The pads contain less silica but more calcium than crucible fragments. Crucible grog was placed in the pads, identified by EDS and visual observation. The pads may have been mixed with local clay or possibly some calcareous fillers.

The analysis of the black glaze on the crucible by EPMA/WDS indicated that its elemental composition is similar to the clay matrix but with a higher percentage of CaO (13%) and MgO (1.5%). This suggests that the black glaze was formed by the reaction of charcoal ash, from the furnace fuel, with the crucible wall. Ash typically contains CaO, MgO, and K_2O (Rye, 1981, 46) in varying proportions depending upon the type of wood used (Percy, 1861, 107-111). The glaze was highly viscous and inhomogeneous, indicated by the areas of different compositions seen in the backscattered image (Figure 22).

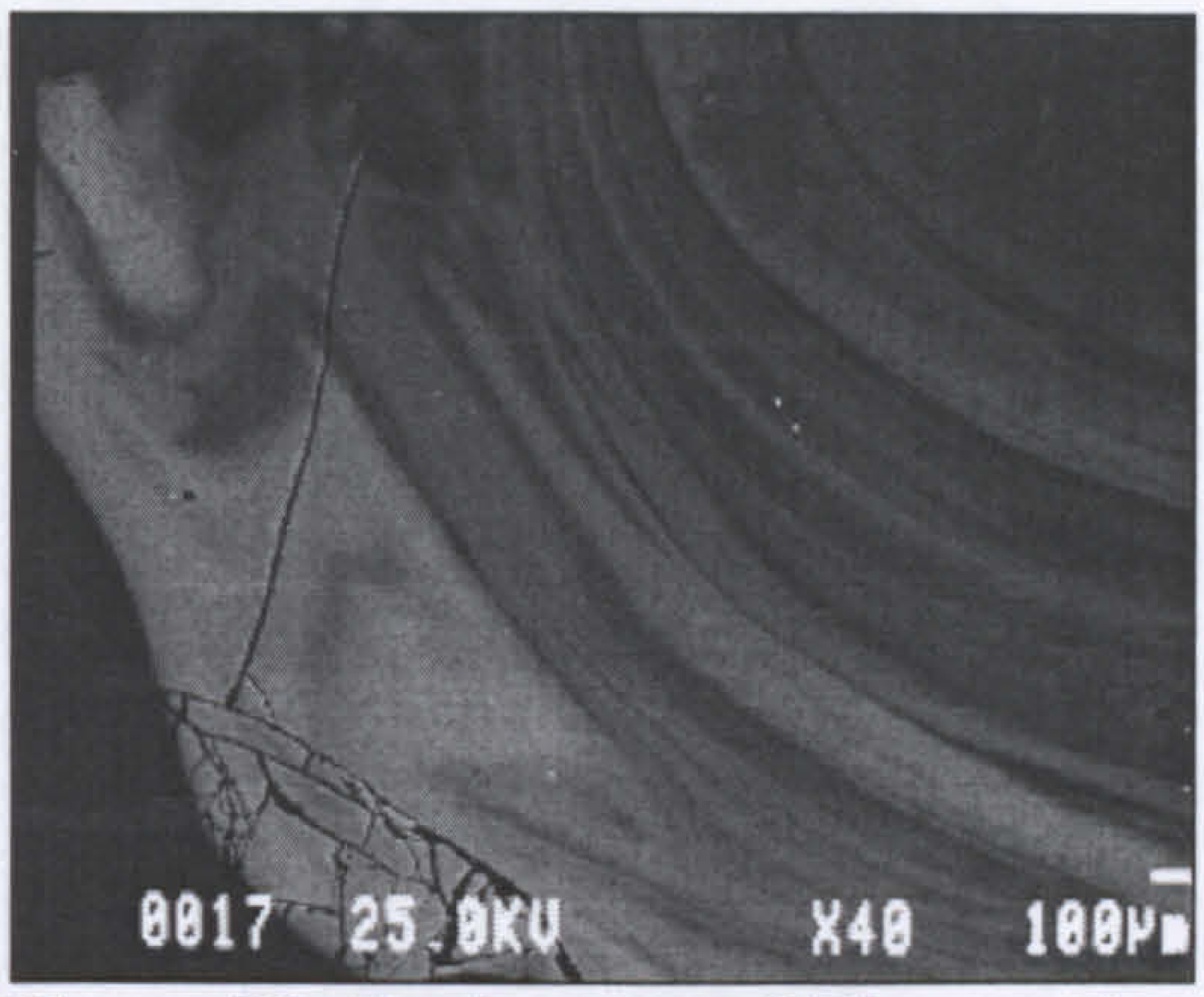


Figure 22: Backscattered Electron image of black glaze showing the differences in composition as lighter and darker grey areas.

Broken crucibles fragments of different sizes were reused in the following ways:

A) As grog in crucible (< 0.2 cm)

B) In pads and in the furnace lining (< 0.5 cm)

C) As the furnace floor (+/- 1 cm)

D) In the furnace walls (> 5 cm)

The relatively consistent size of the fragments used for different purposes indicates sorting of the grog, probably by sieving. The use of grog with no attached prills, slag or black glaze, in the crucibles, but with attached matter in the pad and furnace wall, indicate sorting for size in addition to sorting grog on the basis of any attached extraneous material. They would have had to hand select clean pieces of broken crucible to produce grog for the new crucibles. The glaze and slag would have acted as a fluxing agent reducing the refractoriness of the crucible.

The laboratory examination of the crucible fabrics yielded evidence of variations in porosity, firing temperatures and atmospheric conditions between different areas of the crucibles. Hence, information about the crucibles firing environment and therefore, by direct association, the conditions inside the furnace can be inferred. The entire crucible was made of one type of tempered clay, despite the apparent visual difference between the top part of the crucibles and the base. Indeed it would be detrimental to the process if different tempering materials or clay were used, because the different compositions would undoubtedly have different shrinkage rates and softening points which may cause the crucible to fail, particularly at such high temperatures with extreme temperature gradients. As discussed above, the dark grey upper wall matrix changes to a white matrix with black surfaces as the wall progresses towards the base, which has a completely white matrix. This indicates that the top of the crucible was fired under reducing conditions whereas the base was fired under oxidising conditions. The white interior and black exterior of the central part of the crucible wall, and the complete lack of evidence for organic matter in the crucible body indicates that organic material was not present in the original clay fabric, but was picked up from carbon in the furnace atmosphere (Rye, 1981, 115-116), probably as hydrocarbons (see *Furnaces*). The differences in the degree of vitrification attest to varying temperatures within the furnace. Vitrification is observed most frequently in the crucible's base but is much less pronounced in the upper area of the crucible wall and the lid, indicating that the upper parts of the crucible were fired at a lower temperature.

Furnaces

The remains of four furnaces were uncovered during the excavations. Three of the furnaces (Furnaces 1, 2, 4) are similar to each other. Furnace 3 has a different design. Furnaces 1 and 3 were discovered in 1994, 4 in 1995 and furnace 2 in 1996[5].

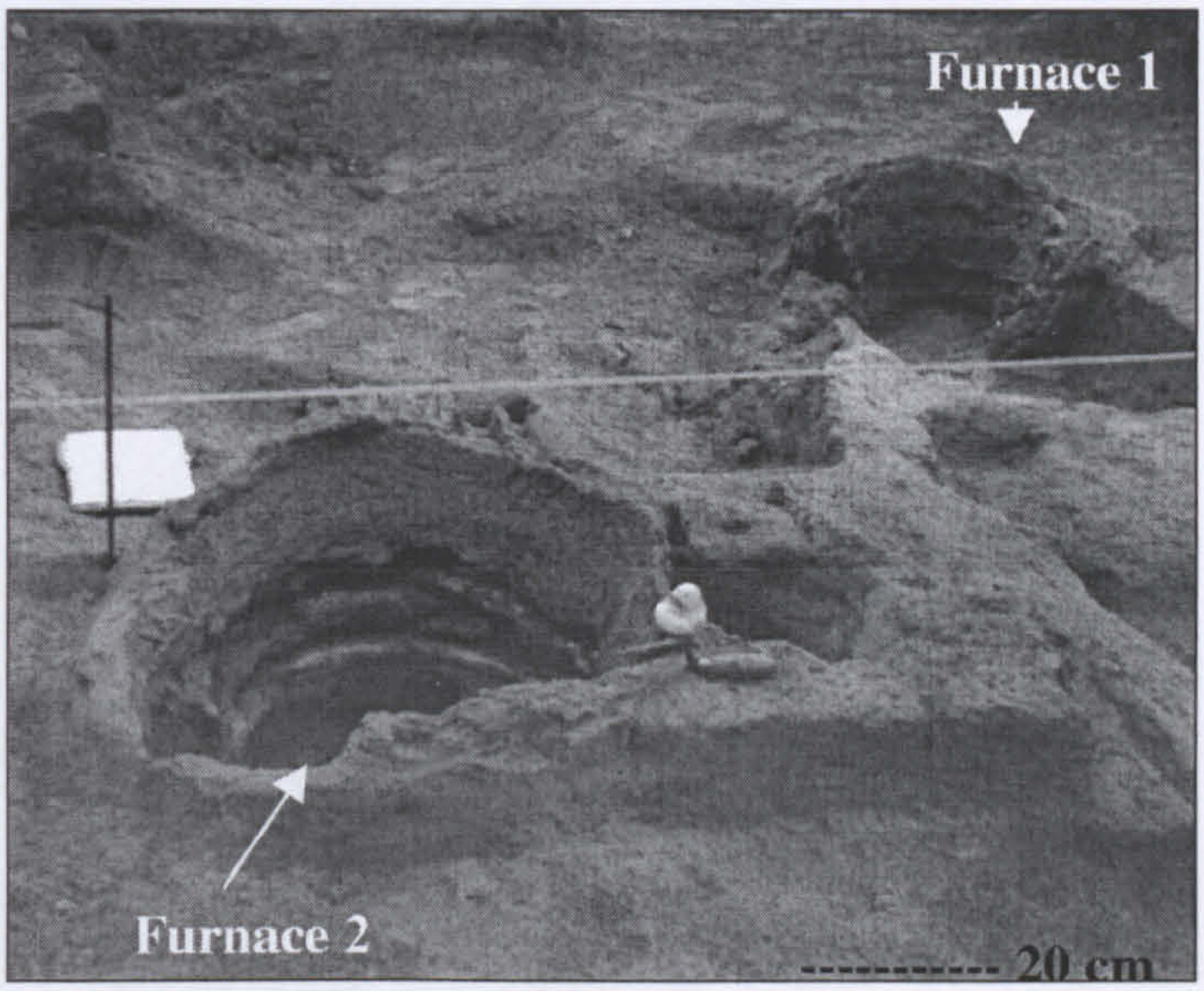


Figure 23: Furnaces 1 and 2.

Furnace 1 was found at a lower level than the other furnaces (Figure 23). The furnace was built into a deliberately cut circular area. Large fragments of Sasanian ceramics were used to line the cut then the furnace walls were built with mud bricks and lined with a ceramic-like material visually similar to the crucible pads. All that remains of the furnace are roughly two-thirds of the circumference consisting of vertical walls 30 to 40 cm high. About a third of the furnace is absent on the southwest side. The external diameter is about 60 cm and a scorched area, observed as an orange ring, is visible beyond the exterior side of the wall. There are three black vitrified layers separated by lining material indicating that the furnace was fired, relined and fired again, at least three times. The final internal diameter of the vitrified interior walls is *c*. 35 cm. The degree of vitrification of the walls is much less pronounced on the upper walls than in the lower regions toward the floor. The original floor level was determined by observing that the

5 Please note that the furnaces are numbered differently in each IRAN report and the forthcoming excavation report by Turner and Powel. I have chosen to use the numbering system used in the 1996 excavation report published in *IRAN* (Herrmann *et al*., 1997, 10).

black glaze on the interior walls abruptly stopped at its thickest point at a specific depth. Attached to this black glaze broken crucible fragments were occasionally detected. Under this presumed floor level, an L-shaped ceramic pipe was found presumably *in situ*. The pipe is made of a white/beige fired clay similar to domestic ceramics found at Merv. Apart from its initial firing during manufacture, the pipe showed no evidence of heat, such as an ash glaze or discoloration. The internal diameter of the pipe is *c.* 5 cm. Presumably the furnace was used as a dump after its use as a furnace ended because broken crucible and furnace fragments and a few pieces of copper-alloy scrap were found inside.

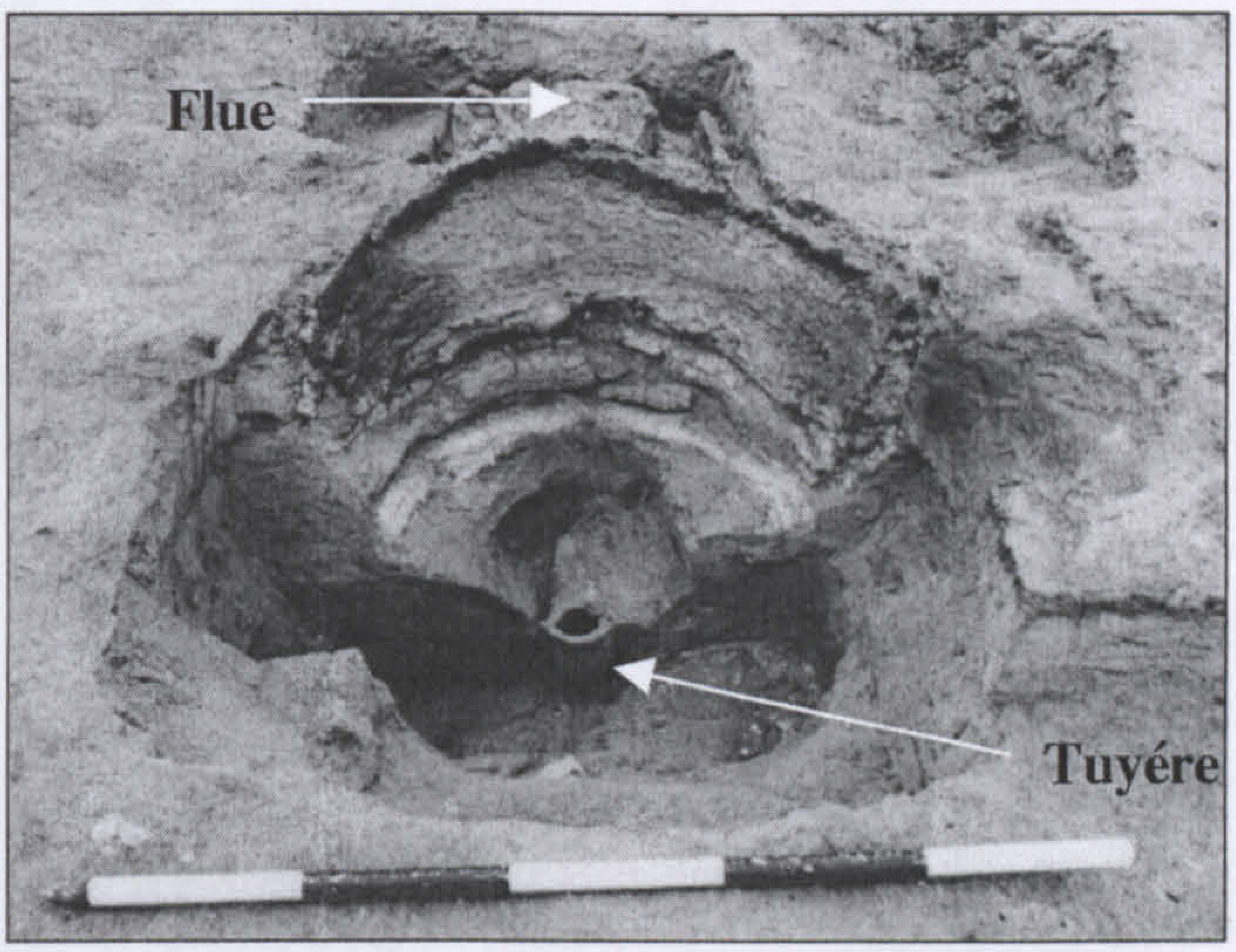


Figure 24: Cross-section of Furnace 2. The length of the scale is one meter.

Furnace 2 (Figure 24) was the best preserved. It was also built of mud bricks in a deliberately cut circular area and had a lining made of crucible grog. The external diameter is *c.* 90 cm. About a third of the furnace wall is missing on the south side. Layers of heavily vitrified walls also exhibit evidence of being fired and then relined with broken crucible fragments for subsequent reuse. Two significant features were preserved: a central pipe (tuyére) and what is presumably an exit flue. The central tuyére was the same as those found in the other two furnaces, 1 and 4. The exit flue is composed of the same mud brick and lining as the body of the furnace. The flue begins at the junction with the furnace body, producing an opening *c.* 20 cm across, and continues for *c.* 20 cm before ending in a pit. The exit flue was interpreted as such because of the extensive vitrification and ash glaze on the walls indicated contact with hot air and ash. The area could have been part of a firebox, however the appearance of the under-floor pipe with no evidence of heating suggested that air was introduced into the furnace through this pipe not via this side extension. The side exit flue was preserved only in this furnace, presumably because the side flue of the other furnaces was destroyed when the crucibles were removed. This additional evidence assisted in the interpretation of the furnaces' mode of operation (see below).

For furnace 4, a pit was cut and then the furnace walls were constructed using greenish clayey triangular and square mud bricks. This is the worst preserved furnace and only the lowest layer of mud brick is preserved. "On the western side of the structure a duct was built which contained the narrow end of a ceramic L-shaped pipe with a flaring end placed upright in the centre of the brick circle" (Turner and Powell, forthcoming). The bricks on the top of this duct are heavily vitrified. The 'duct' may have originally been the floor at the bottom of the exit flue from earlier firings. This is suggested by the similar orientation of the tuyére, underneath the previously used exit flue, in furnace 2.

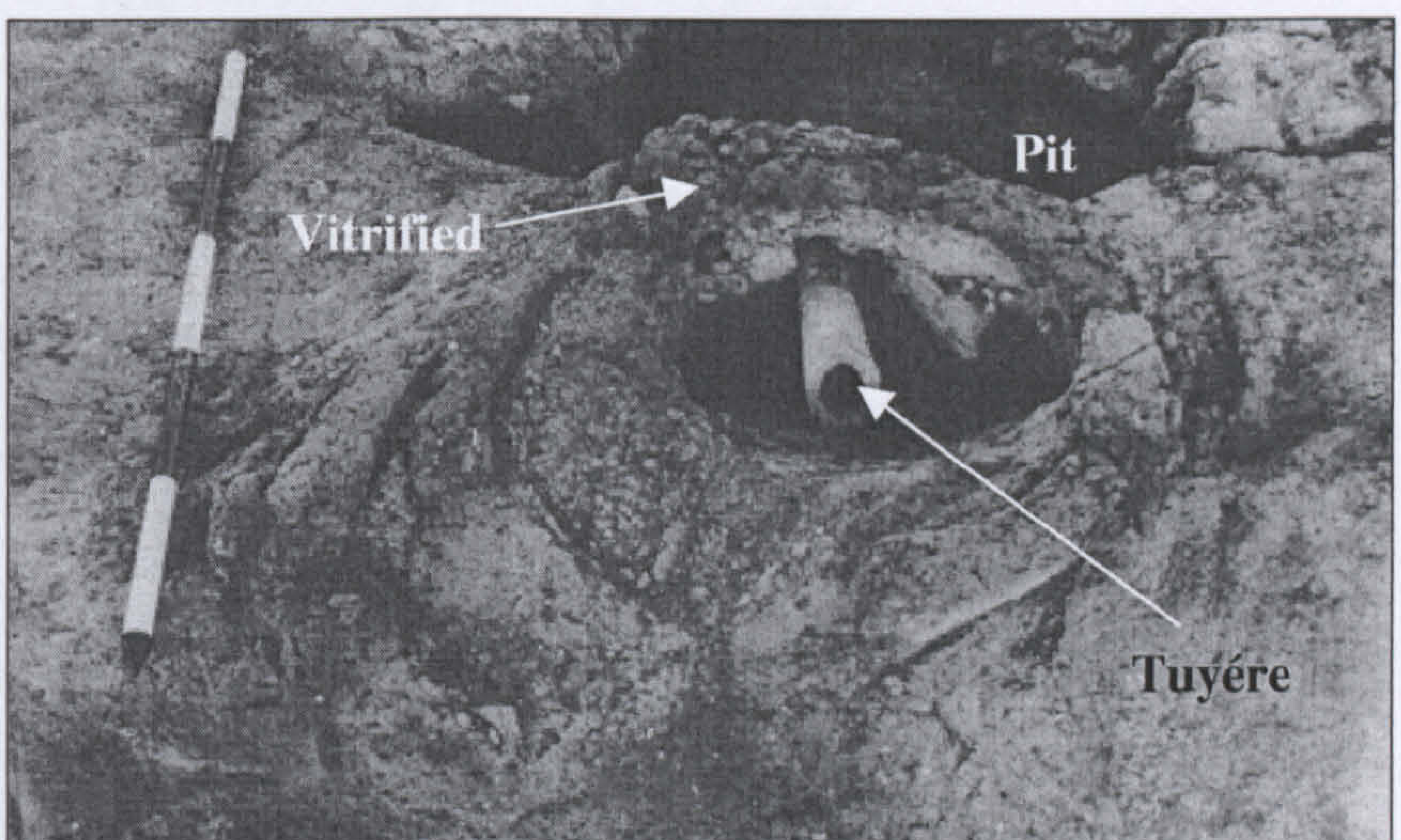
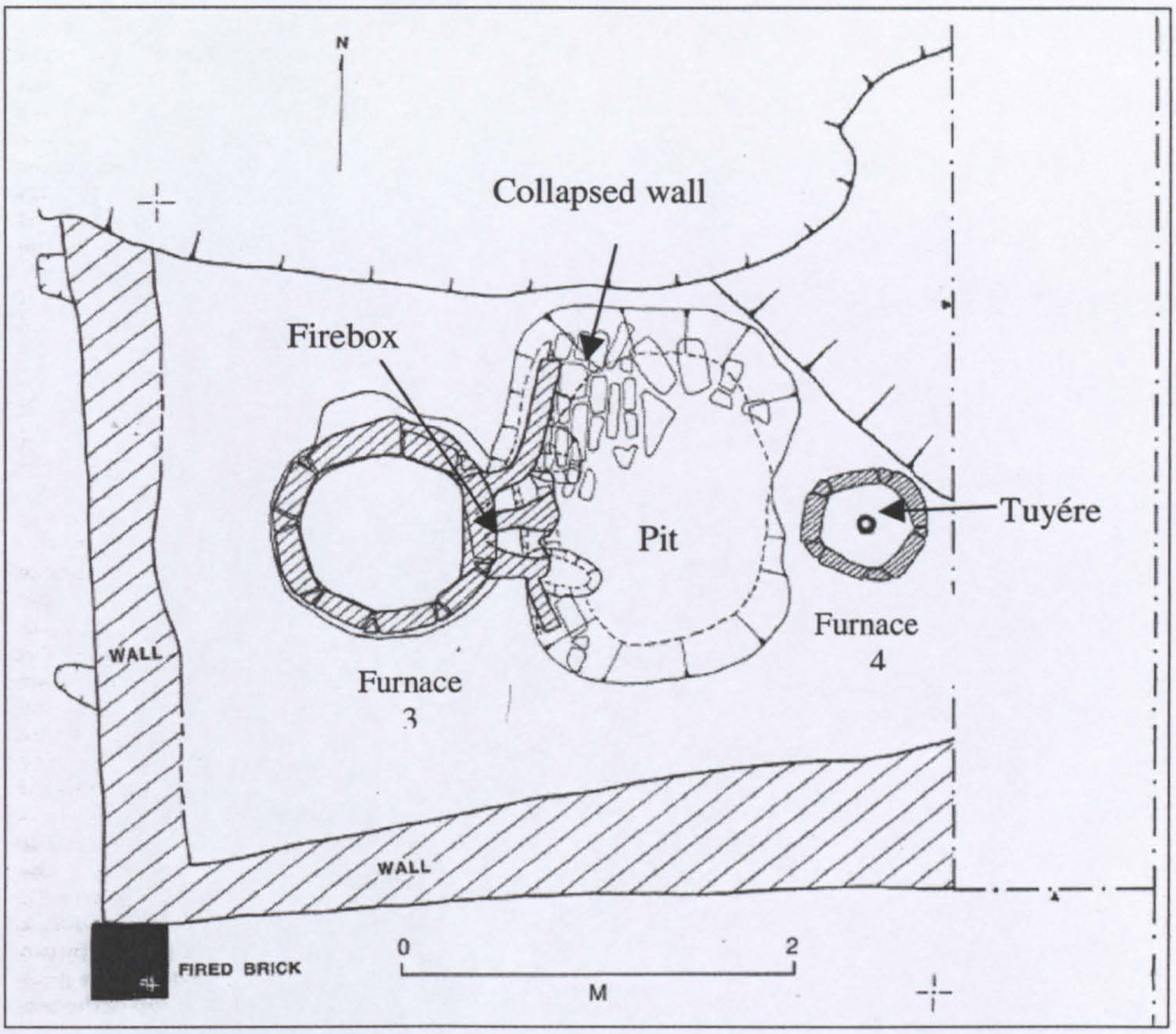


Figure 25: Furnace 4 with tuyére; 1 meter scale (from Herrmann *et al.*, 1997).



Map 7: Plan of Furnaces 3 and 4 (from Herrmann *et al.*, 1997, 12).

Furnace 3 was found near present surface level as a circular feature of highly vitrified material *c.* 10 cm thick and *c.* 10 to 15 cm high. Adjacent to the outer edge of the vitrified material was an orange ring of soil 7 cm wide. The remains of the vitrified material were approximately 70 cm interior diameter, with about a quarter of the vitrified lining material and the orange area, missing on the northwest side. Further excavation revealed that it had an atypical design (Map 7 and Figures 25 and 26). The furnace consisted of the furnace proper and an attached "firebox" next to a pit. The furnace was set in a pit 1.9 m x 1.6 m. The furnace was 80 cm in external diameter and constructed of greenish (high clay) mud brick with smaller triangular inserts. These inserts were also made of clay and had evidence of scorching. The "firebox" was 60 x 40 x 25 cm and was pierced by two holes running east/west and narrowing at the junction with the furnace, apparently used to support two bellows. The interior top of the box was vitrified, but not the sides or bottom. Presumably this is because the floor of the firebox was cleaned out along with any residual ash/charcoal but the top was affected by the heat and ash causing a vitrified and slightly glazed layer to form, preserving evidence of firing. This furnace is furnace is assumed to be a blacksmithing hearth because it has a different construction than the crucible furnaces and the presence of a "firebox". However, it may have also been used to anneal the crucible ingots (see *Iron and Steel* below). Remains of a wall are interpreted as being a shield wall, presumably separating the bellows operator from the furnace (Turner and Powell, forthcoming). It is likely that the bellows operator was in the pit adjacent to the furnace box.

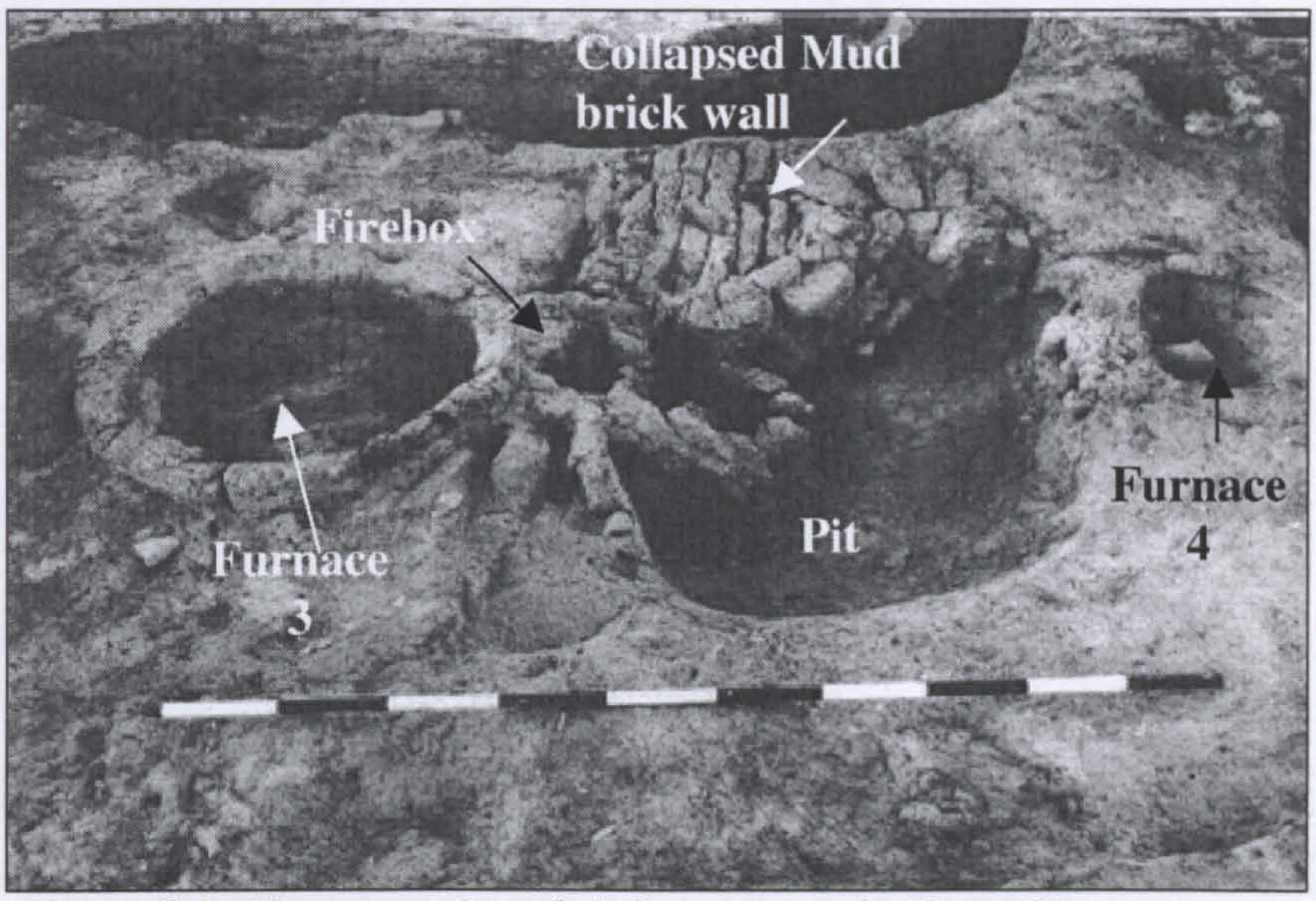


Figure 26: Furnaces 3 and 4; 2 meter scale (from Herrmann *et al.*, 1997)

The furnaces were primarily constructed of mud bricks with added organic temper, which is clearly visible in some samples (Figure 27). A lining was applied to the interior of the furnace wall. The lining is visually similar to the materials used for the crucible pads and contains a large quantity of crucible grog about 0.5 cm in diameter (Figure 28). It was observed that this layer is thicker at the bottom of the furnace than on the upper areas.

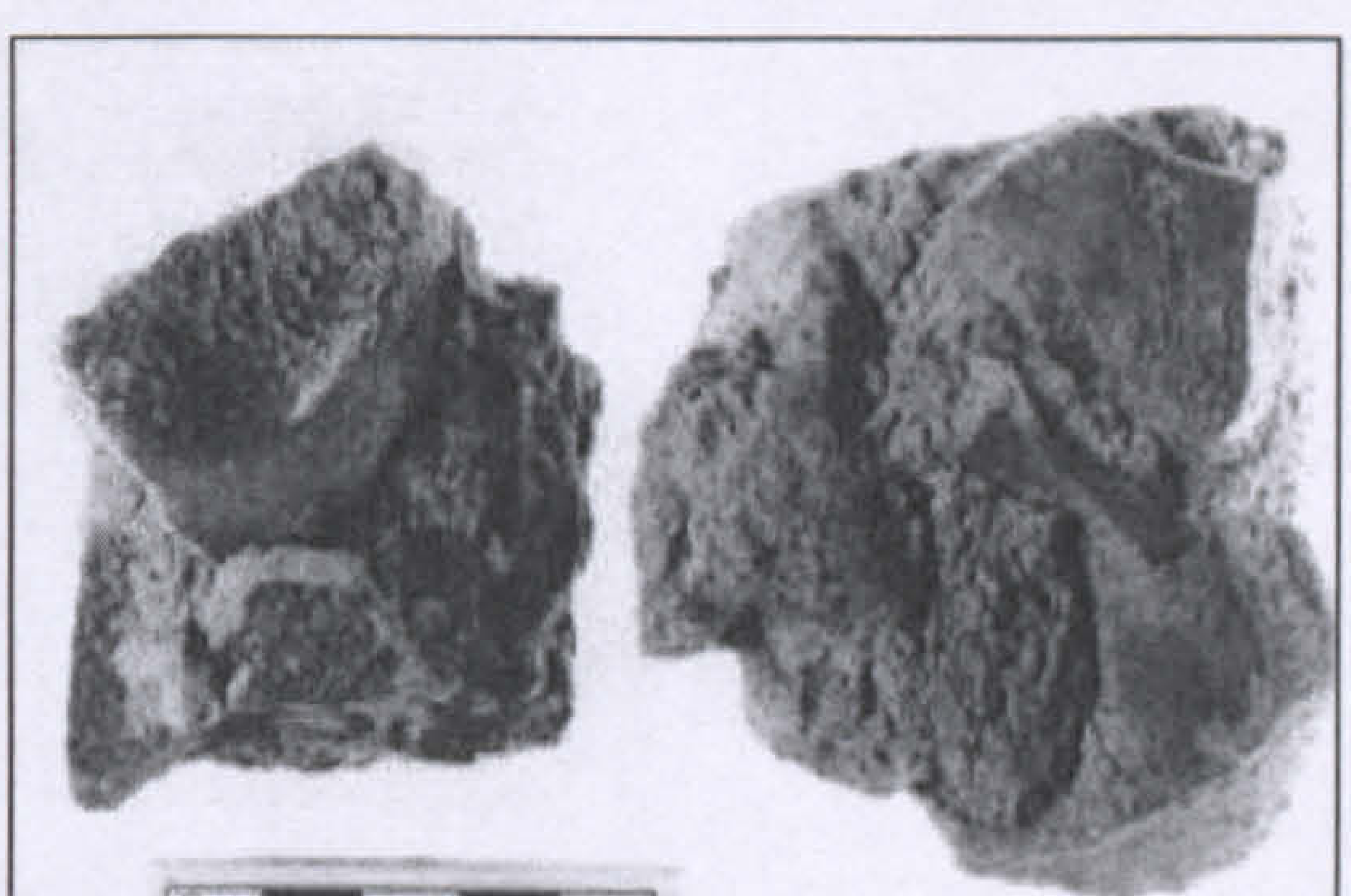


Figure 27: Furnace wall with large crucible fragments.

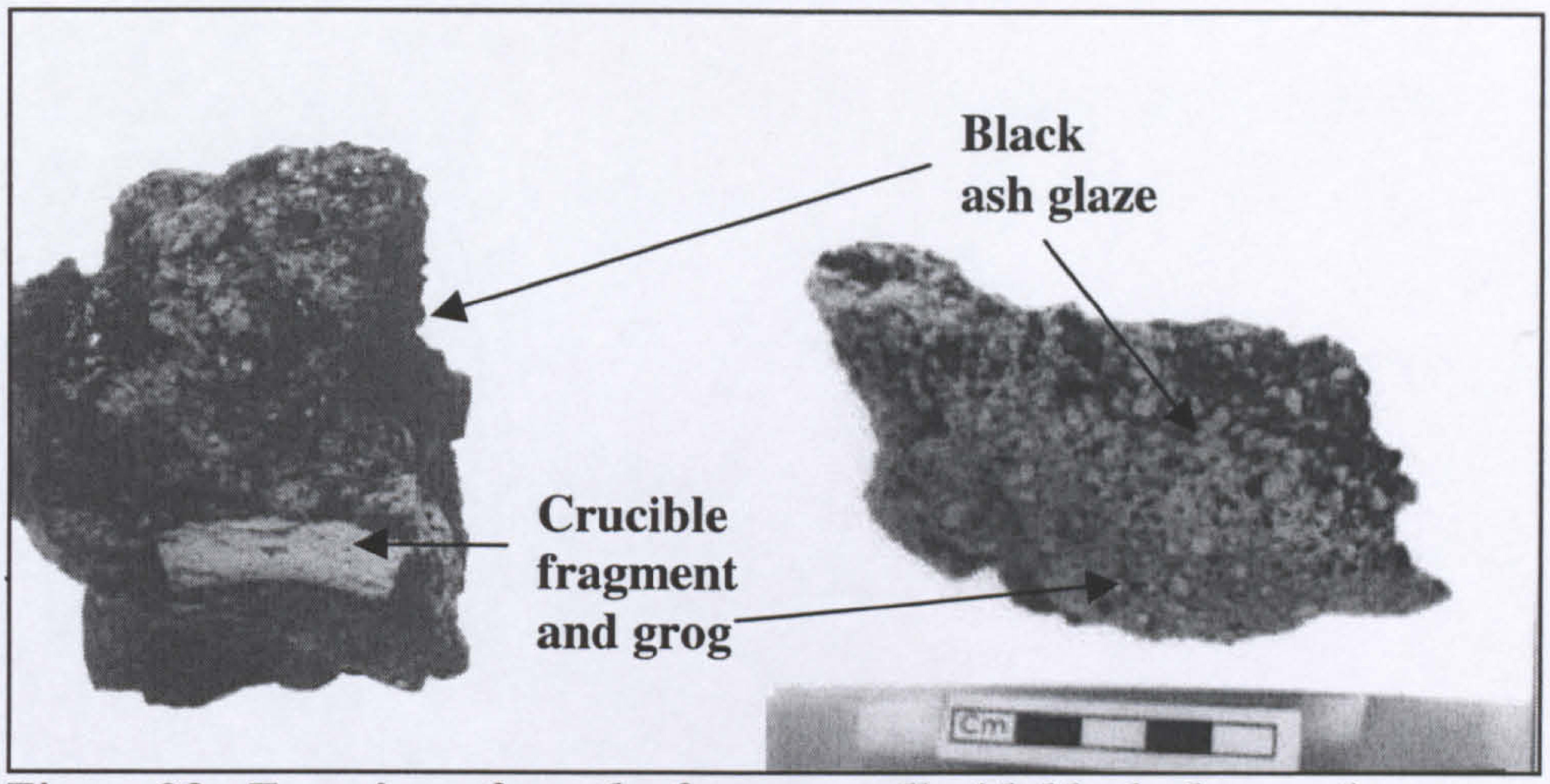


Figure 28: Two pieces from the furnace wall with black glaze and grog.

The upper areas of the interior furnace wall where the lining becomes thinner, has a black crumbly texture that transforms into a black glaze towards the bottom of the furnace. The glaze becomes progressively thicker towards the bottom of the furnace. The elemental composition of the black glaze determined by EDS is consistent with the black glaze that appears on the exterior of the crucibles and on the furnace floor fragments. The results of the elemental analysis indicated a higher level of Mg and Ca in the black glaze than in the furnace wall, suggesting that the black glaze is consistent with the composition of an ash glaze caused by the reaction of the fuel ash acting as a fluxing agent with the siliceous components of the furnace lining.

Pieces of the furnace floor were found in the crucible pit but not *in situ* in the furnace although evidence for its location was observed. The black glaze on the interior walls abruptly stopped at its thickest point at the bottom of the walls around the periphery of the furnace, occasionally a small broken crucible fragments were attached to this glaze. Broken crucible pieces used to line the furnace floor were found attached to the furnace wall by a thick black glaze (Figure 29). EDS (peak chart) indicated that the black glaze the furnace walls was composed primarily of Si, with some Al, Ca, and Mg, a similar composition to the sides of the crucibles. Parts of the furnace floor still attached to some crucible pads suggest that broken crucible fragments were spread on the floor of the furnace, between the crucibles. The broken crucible pieces prevented the crucibles from firing to the bottom of the furnace by creating an insulating layer, providing an uneven surface for the black ash glaze to flow on top of creating a breakable and comparatively easily removable furnace floor, and assisting the movement of air within the furnace by creating turbulence.

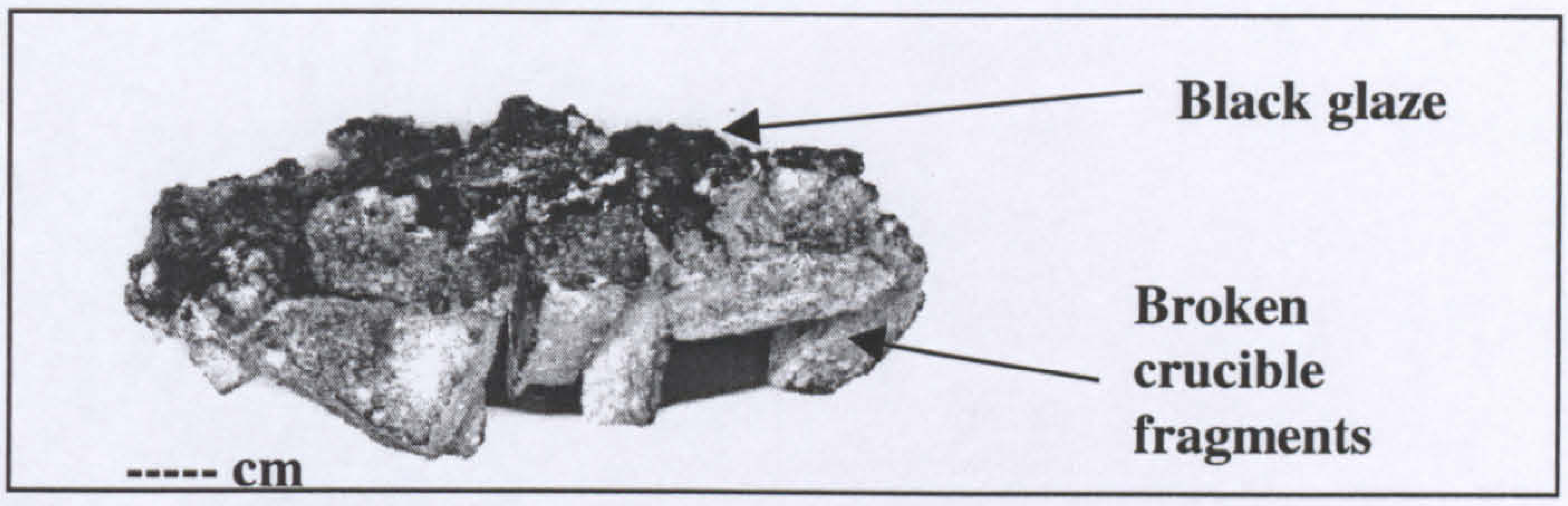


Figure 29: Furnace Floor (previously called Refractory Mass).

The close proximity of the crucible pit and the mud bricks occasionally containing broken crucible pieces indicate at least some association with the crucible steel process. The furnaces are deep enough to contain crucibles and enough charcoal to cover the crucibles. In addition, the use of broken crucible fragments in the furnaces construction suggested that they were used for the crucible steel process. The conclusion that the furnaces were used in the crucible steel process is based on the following evidence:

1) That broken crucible pieces were found attached to a black glaze at the junction of the furnace wall and floor and attached to crucible pads,

2) The extensive use of crucible fragments and grog in the furnace construction,

3) The similar appearance of the furnace lining and crucible pads,

4) The similar elemental composition of the black glaze of the interior of the furnace walls and the exterior of crucibles and pads,

5) The close proximity of the crucible pit to the furnaces, and

6) The lack of evidence for any other objects that might have been heated in the furnaces.

The average diameter of the three furnaces at the exterior walls was between 70 and 95 cm across, while the interior ranged from *c.* 30 to 50 cm producing an initial wall thickness of about 10 cm which was subsequently thickened by relining, thus reducing the interior diameter. The smaller furnace could hold a maximum of 7 crucibles while the larger could have held 20 maximum. The number was probably one or two lower when one considers that the crucibles were not touching each other and probably had charcoal in between them, or at least ash, indicated by the thick glaze.

The walls were vertical and their height was at least 40 cm, as this amount is preserved in one of the furnace. A complete furnace wall would have needed to be high enough to contain the necessary amount of (presumably) charcoal, unless more was added during the process but that would have been inefficient and the temperature would have decreased while it was being added, resulting in the use of even more fuel. Excess in height would have also been inefficient due to a higher surface area and more air to heat to a sufficient temperature. Therefore, it is estimated that the height was probably not far above 40 cm. The height of a crucible is around 20 cm, half the height of the furnace, thus leaving the areas between the crucibles and around 20 cm above them for charcoal.

The design and operation of the furnace can be suggested by comparing the visual archaeological evidence to known furnace parameters (Figure 30). Although no archaeological evidence remains of the top part of the furnace, it is reconstructed as a closed top domed furnace with a central tuyére rising up from the floor of the furnace, and with a side exit flue, based on the following evidence.

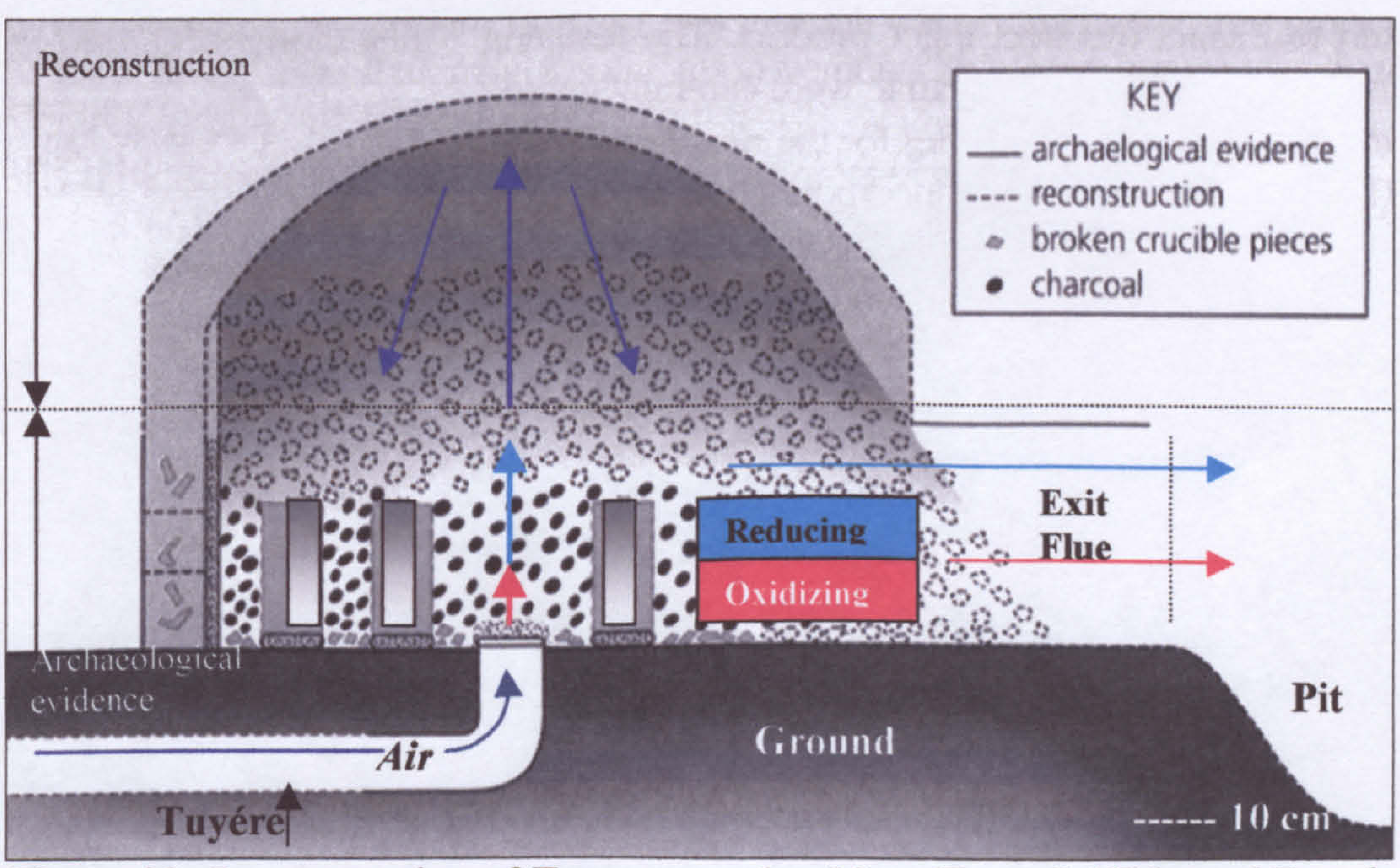


Figure 30: Reconstruction of Furnace used at Merv (From Griffiths and Feuerbach, 1999, 473).

Three of the furnaces had a central air pipe rising out of the centre of the floor of the furnace. This is interpreted as the tuyére and presumably this was attached to bellows needed to blow air into the furnace to raise the temperature high enough for the crucible steel process to work. The air would have come through the tuyére at the bottom of the furnace and travelled up through the charcoal. It is unlikely that the necessary temperatures, at least over 1050 ^{O}C suggested by the presence of mullite and probably over 1450^{O}C (see *Iron and Steel*) would have been reached and maintained, presumably for hours, using an open top furnace.

Furnace 2 had a section of the furnace wall that splayed out from the body of the furnace. The internal walls of the splayed area exhibited a high degree of vitrification, equal to the thickest glaze at the bottom part of the furnace near the floor. This indicates that hot air and ash from the fire was somehow directed into this area. If the exit flue was directly above the tuyére and there was no roof, the air would have blown out of the furnace top and would not have vitrified the splayed area nor heated the crucibles sufficiently. By having the flue on the side, the air would come up out of the tuyére, circulate around the crucibles and fuel before leaving through the flue, thus more evenly distributing the heat around the crucibles. The furnace works both as an updraft and a down draft furnace. Therefore, to satisfy the archaeological observations, and for the furnaces to reach and maintain the necessary temperatures, the top of the furnace had to be closed. A domed roof is suggested rather than a flat one because it is the most efficient shape for heat distribution and is mechanically more stable. In addition, there is archaeological and ethnographic evidence of pottery kilns that support the suggested furnace reconstruction (see below).

After the firing and the cooling of the furnace, the furnace was broken into on one side and the crucibles were removed. The sharp breaks in the black glaze around the crucible pad imply that the glaze was brittle when separated from the rest of the furnace floor. In addition, the evidence of slow cooled steel prills in the crucible slag (see *Iron and Steel* below) indicate that the crucible contents, and therefore by association, the crucibles themselves were slowly cooled. The furnaces were then relined and used again.

The black glaze on the crucibles, furnace floor and furnace wall indicate that they all were in direct contact with the fuel. The fuel was probably charcoal, rather than wood or a mineral fuel such as coal. There was no archaeological evidence, such as unused or partially combusted pieces, indicating the use of a mineral fuel at Merv but there are pieces of charcoal found in the furnace wall as well as in the crucible pits. The charcoal most frequently identified by Gale (forthcoming) was pistachio (*Pistacia*). In order of frequency reported, were members of Chenopodiaceae, Tamarisk (*Tamarix*) and willow/poplar (*Salix/Populus*). Less frequently found were elm (*Ulmus*), species of Prunus, members of Pomoideae (apple/pear/ hawthorm group), juniper (*Juniperus*), *Ephedra*, mulberry (*Morus*) or *Celtis* (Gale, forthcoming). Charcoal was probably used because it burns cleaner, takes up less space, and burns hotter than dry wood. For details of the properties of different types of charcoal see Percy (1861, 107-111). However, one would only expect carburized wood to have survived over time therefore any remains of dry wood fuel, if it was used, are unlikely to remain.

After building the furnace, the crucibles were placed inside. Next, broken crucible pieces would have been placed in between the crucibles and charcoal would have been put around the crucibles. The furnace roof would have been sealed before the fire was started. Bellows must have been used to introduce air into the fuel bed via the tuyére, as no natural draft would develop. The most effective placement for the tuyére would have been to introduce the air a few centimetres in to the fuel, and this is where it is located in the Merv furnaces. In this way more air is distributed in the fuel bed and less air escapes up the furnace wall (Rehder, 1987, 53).

The design of the furnace would have been very efficient, utilising many of the same principles as deep fuel bed furnaces and modern gas producer furnaces (Figure 31). It is the oxidation and reduction zones of the burning deep fuel bed of the gas producer furnaces, which can be compared to the mechanism that would have occurred in the Merv furnaces. Evidence provided by the crucibles and the reconstructed furnace design can suggests the furnaces' mode of operation and efficiency. After the furnace was fired for a period of time, an ash bed would build up at the bottom. This is evident from the black ash glaze at the base of the furnace and over the furnace floor. The introduction of air into the incandescent ash at the bottom of the fuel bed would produce an oxidation zone. According to the Ministry of Power (1958, 427) the depth of the oxidation zone is 3-5 times the average particle diameter of the fuel and the temperature reached by the fuel in this zone is the highest in the fuel bed, which may reach 1600^{0} C.

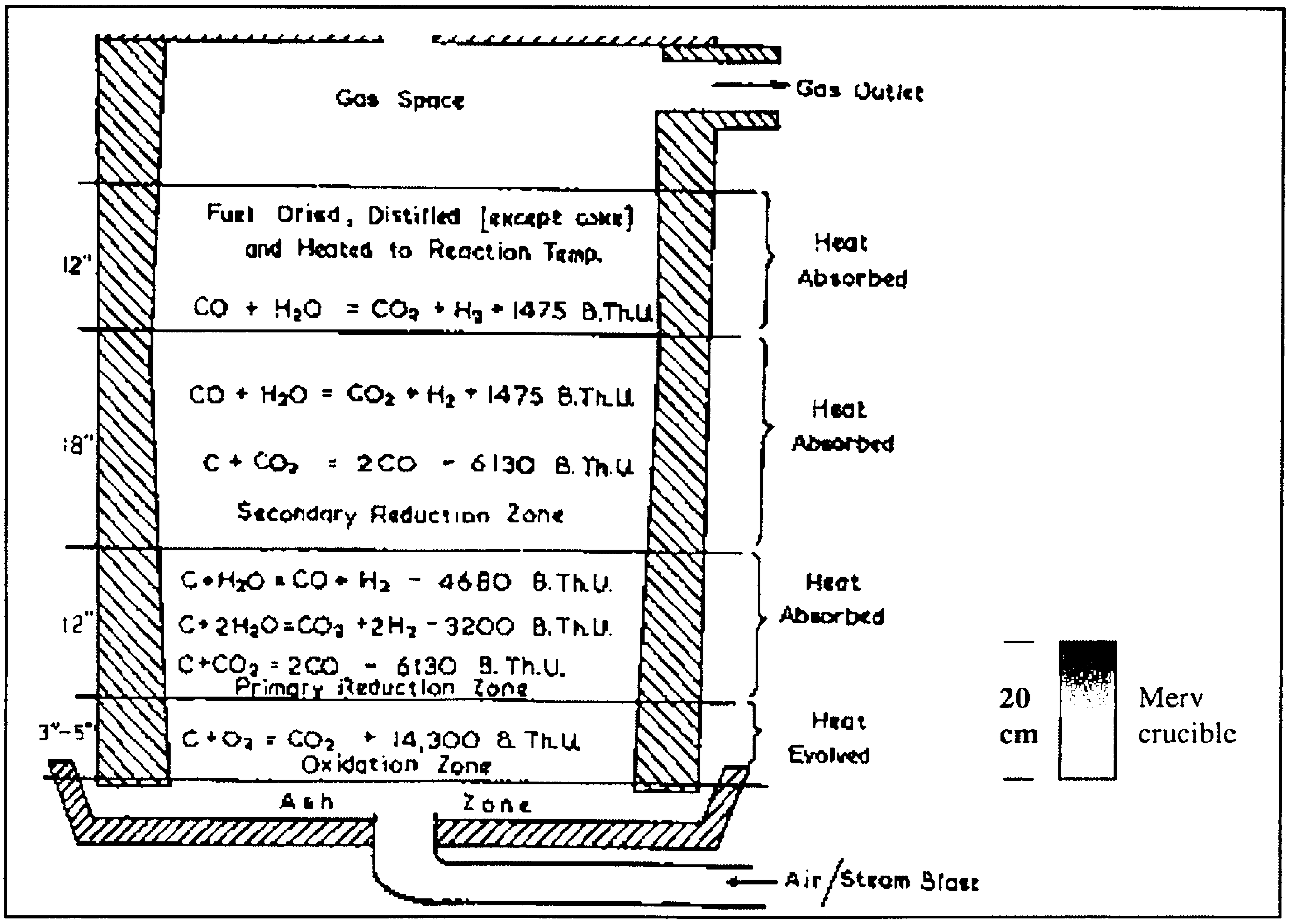


Figure 31: Reactions in a deep fuel bed compared to crucible from Merv.
(Clews, 1955, 174)

The evidence found in the crucibles supports this. The crucible bases have a white matrix, indicating that they were fired under oxidising conditions and the degree of vitrification and ratio of glass to ceramic in the matrix indicated that it was also the highest fired part of the crucible. In addition, by measuring the average height of the white crucible matrix, the oxidation layer in the furnace is approximated at about 8 cm from the floor of the furnace. Based on the Ministry of Powers claim (above) the average size of the charcoal would have been between 1.6 -2.6 cm in diameter.

All the oxygen would quickly be used up as the air travels up through the fuel bed and would enter a reduction zone where the temperature would drop from around 1,100^{O}C at the bottom of the reduction zone to around 800 ^{O}C at the top of the reduction zone (Ministry of Power, 1958, 430). This steep drop in temperature and the presence of a reduction zone can be observed as the dark grey, lower fired upper areas of the crucible wall and lid.

Although direct evidence cannot be observed from the archaeological remains, evidence that the furnace produced and burned its own gas can be deduced from the above evidence of a deep fuel bed. Modern gas producer furnaces usually used coal or coke but charcoal could also be used (Ministry of Power, 1958, 426). A gas producer furnace uses a deep fuel bed with added water vapour to assist in the production of hydrocarbons.

The Merv furnaces also utilised a deep fuel bed, indicated by the evidence provided by the crucible, and water vapour would have been present from the crucibles loosing water when they were being fired, in addition, some water vapour would have come from the charcoal. Charcoal readily absorbs water vapour from the atmosphere. The amount it will absorb is dependent upon the size of the charcoal, the atmospheric moisture, and the temperature at which the charcoal was produced. The temperature at which it was produced will also effect how easily the charcoal ignites. Provided the charcoal was dry enough to fire, the amount of water vapour and steam present in the furnace would not have significantly affected the furnace operation however under certain conditions it would have contributed to the production of hydrocarbons as one of the gaseous products. When the blast of air reached the reduction zone, the water vapour and unreacted carbon would form hydrocarbons and carbon monoxide (Ministry of Power, 1958, 430).

These hydrocarbons would be forced upwards by the new incoming blast of air, then, if the furnace had a closed top as suggested, the gas would flow downwards again before going out of the flue. At least some of this hot gas would be forced back into the hot charcoal and would combust as a gaseous fuel providing additional heat to the furnace. These hydrocarbons would also transport carbon into the fabric of the top part of the crucible, giving rise to the black lid and upper parts of the wall.

While the craftsmen would not know about this hydrocarbon containing gas, they probably would have noticed that less fuel was needed with this furnace design and that it reached the high temperature needed for the crucible steel process to function. The implications are that less fuel would have been needed, thus a reduction in production costs for the craftsmen, a necessary consideration at Merv, a city with little natural vegetation.

Features of the proposed furnace reconstruction are supported by ethnographic observations. Wulff illustrates the design of three pottery kilns that he observed being used in Persia during the 20th century (1966, 158-160). Each of these furnaces has certain features that are not dissimilar to the proposed furnace reconstruction. A kiln from Sāh Rezā is similar to the proposed reconstruction because it is an updraft kiln (Figure 32). Secondly, a central hole in the floor is used to introduce air into the kiln. In this kiln the air is heated before entering the firing chamber, which differs from the Merv kiln, which introduces ambient air into the firing chamber where it is subsequently heated. There are no side exit flues but a single hole in a domed roof where the air exits the kiln.

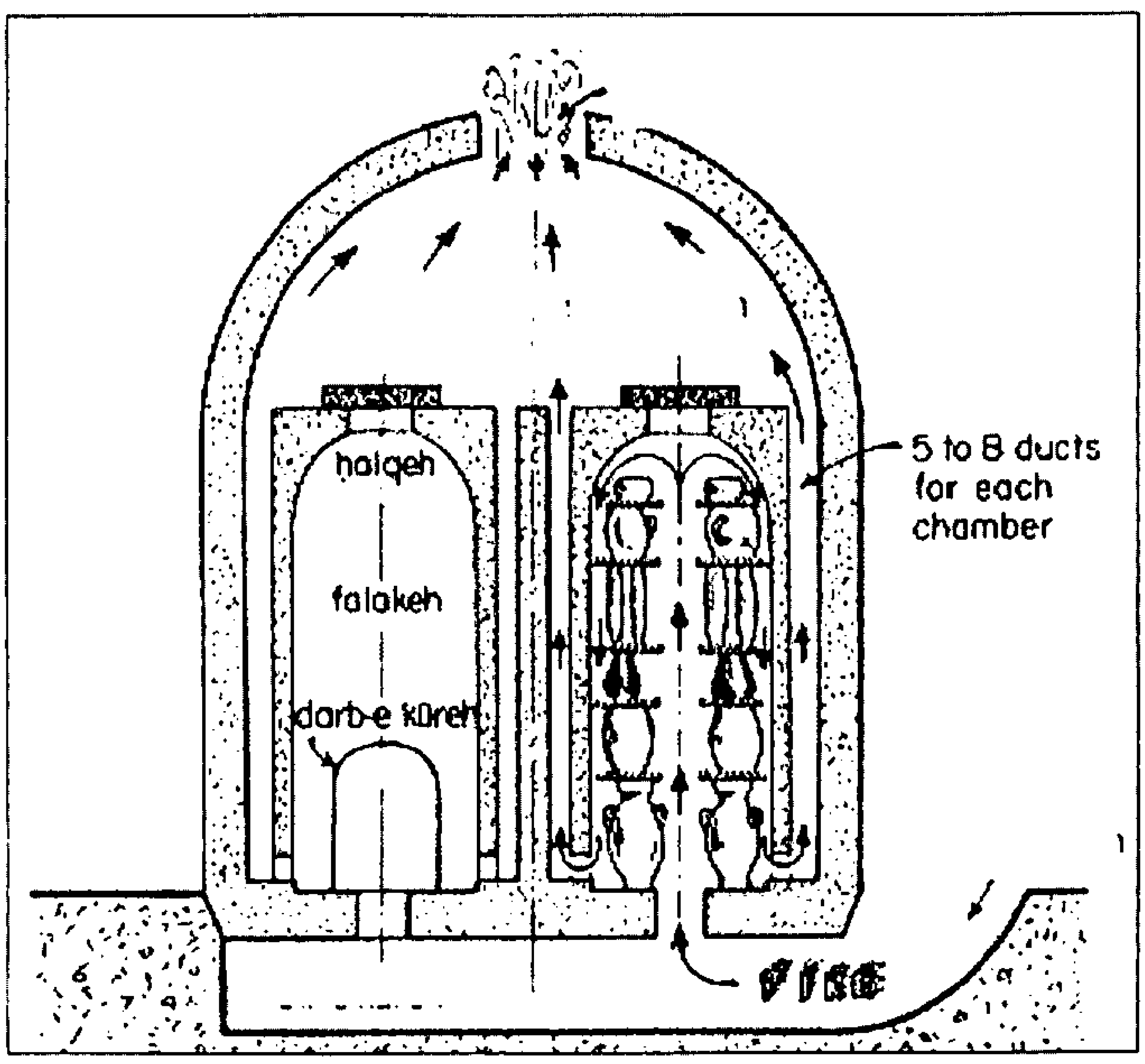


Figure 32: Pottery kiln from Sāh Rezā (from Wulff, 1966, 159).

Of particular interest is a kiln from Bīdoht in the Khurasan region (Figure 33). The kiln operates as a down-draft kiln. There is a fire pit on one side that obtains air from an underground duct. On the side opposite the fire pit, ground level exit flues lead into chimneys. According to Wulff, "This means that the combustion gases first rise through the stacked ware to the vaulted ceiling and are then forced to descend to ground level in order to escape through the chimney openings. The speed of the gases is considerably reduced through the down-draft, and more efficient heating is achieved" (1966, 160). The similarities with the reconstructed Merv furnace is the enclosed domed roof, ground level flues and the use of a down-draft which heats the vessels when the air travels into the firing chamber and on the way out of the furnace.

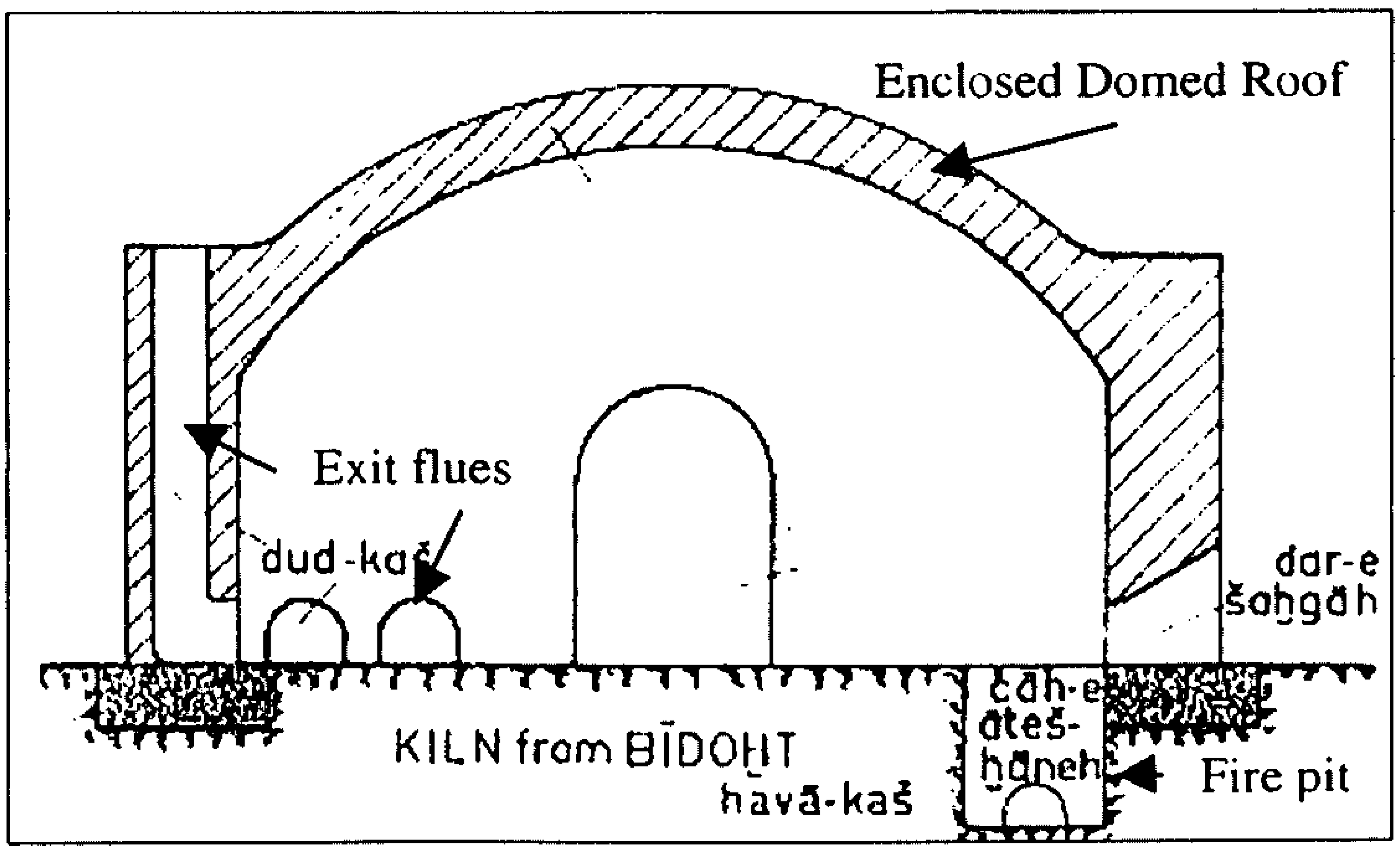


Figure 33: Kiln from Bīdoht (from Wulff, 1966, 160).

Another pottery kiln from Persia also had a domed roof and side flues further supporting the proposed reconstruction (Figure 34). Wulff does not state where he observed the kiln being used but it is undoubtedly in Persia. The domed roof is enclosed but this time the exit flues are near the roof, rather than at ground level. The heated air flows up through holes in the floor to fire the vessels. The air reaches the domed roof, then travels down the sides of the roof and out through the side exit flues, similar to the Merv furnace reconstruction.

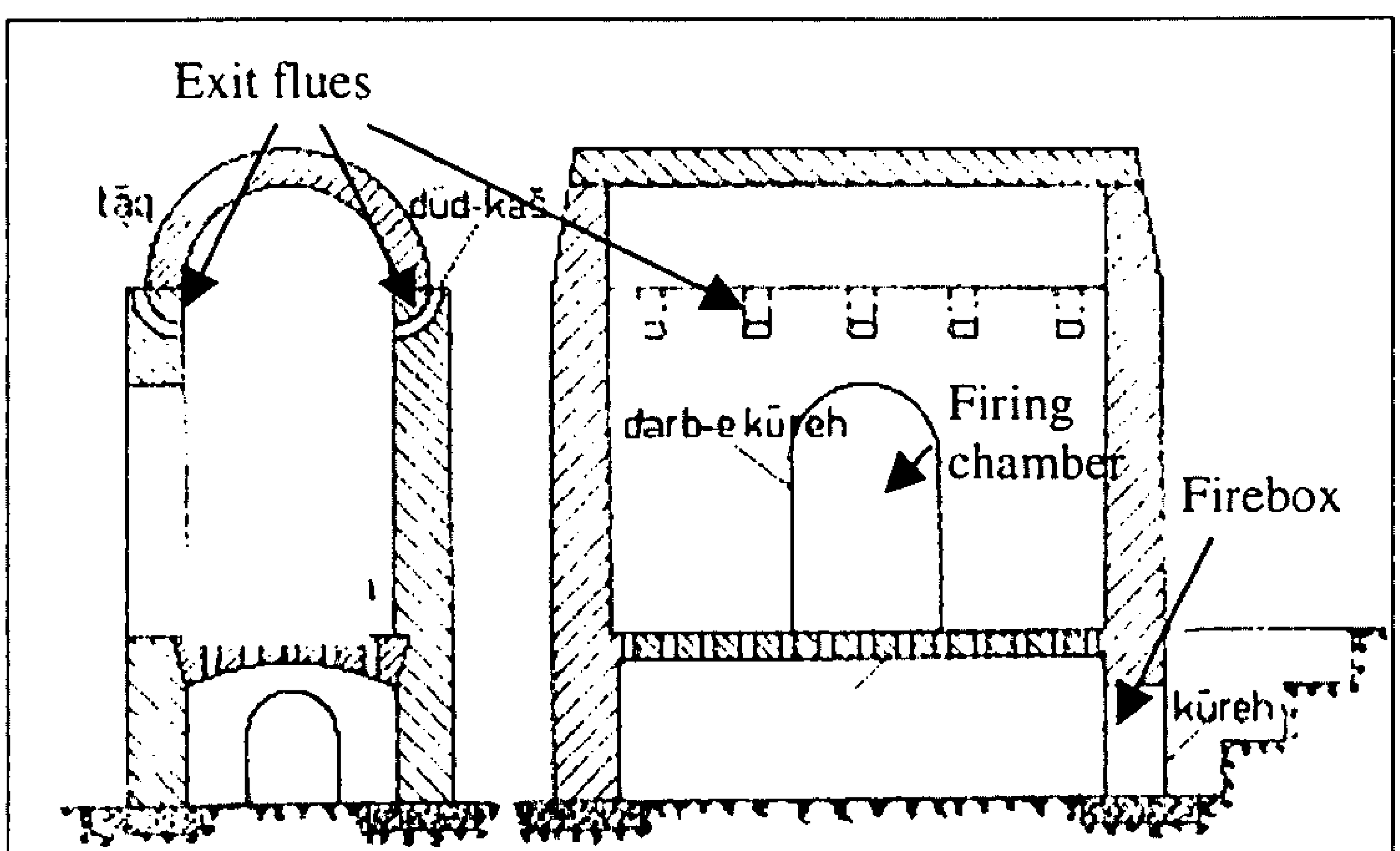


Figure 34: A pottery kiln with side domed roof and side exit flues (from Wulff, 1966, 159).

Furthermore, archaeological examples of pottery kilns with an outwardly similar design have been excavated from 7th and 8th century contexts at Merv, in Gyaur Kala. One type is reconstructed as up-draft kilns with firebox attached to one side, and an exit flue at the centre of a domed roof (Figure 35).

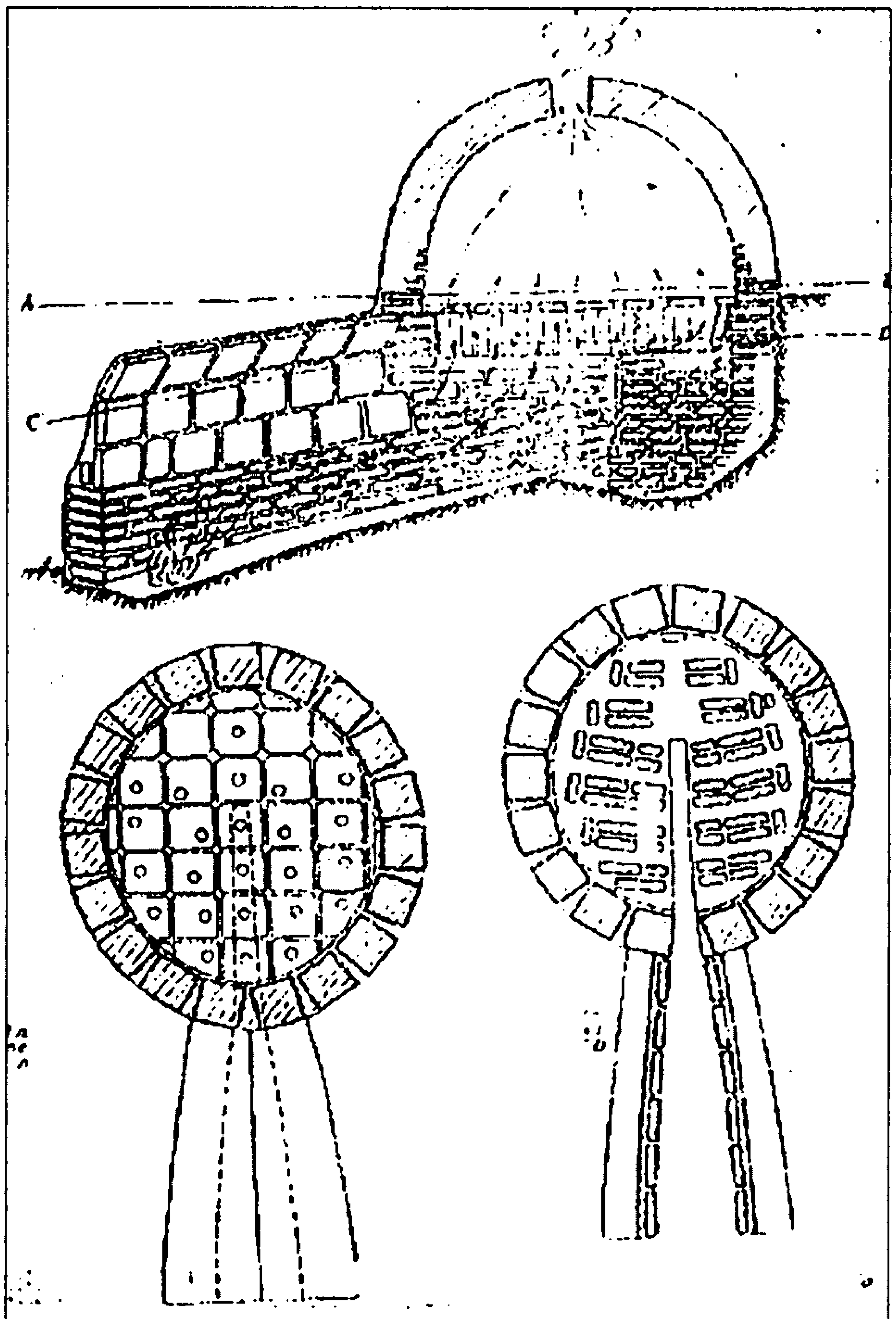


Figure 35: Example of 7th –8th century AD pottery kilns from Merv (Эаурова, 1962,171).

The design of this type of kiln is superficially similar to the proposed reconstructed crucible steel furnace, in that they are both circular, are interpreted as having a domed roof, and there is a vitrified section that juts out from the body of the furnace. However, the crucible steel furnace would function in a very different way because of the tuyére situated in the centre of the furnace floor. This kiln presumably utilises a natural draft indicated by the firebox and the hole in the roof. The crucible steel furnace presumably had a forced draft provided by bellows. Therefore, although both the kiln and the furnace were used to fire ceramic vessels and have a similar outward appearance, their mode of operation is very different.

Crucible Slag

Crucible slag was found attached to the interior of the crucible walls and as loose pieces detached from the crucible wall (Figure 36). The vast majority of the crucible slag was found during the surface survey and excavation around the crucible pit. Their non-deteriorated appearance suggests a high resistance to weathering. The slag ranges in appearance from a shiny, translucent "bottle" green to a darker, duller bluish green. Most samples match the former description and there is no correlation between the colour and the elemental composition (see below). A few samples exhibit a reddish-brown swirling streak on the slags top surface, but this is rare while other pieces exhibit "rusty" spots and cracks, presumably from corroded iron/steel.

Figure 36: Loose pieces of crucible slag. The light brown areas are small sand particles from the burial environment and now trapped in the vesicles.

The largest pieces are about 1 cm in length, 0.7 cm in width, and 0.5 cm at the thickest area, and *c.* 0.05 cm at the thinnest. The slag is smooth on the upper surface, but has semi-circular holes, *c.* 0.4 mm in diameter, on the underside. The slag solidified in a fin-like shape and is assumed to have formed during cooling, after floating as a liquid on top of a convex meniscus, presumably the steel ingot (see *Iron and Steel* below). The shape was caused by surface tension during the cooling and subsequent solidification and contraction of the steel below, which would have solidified before the slag. The contact angle between the wall and the slag on most fragments is *c.* 120-130^{O} (Figure 37), indicating a non-wetting slag. However, the contact angle between some samples was less than 90^{O} indicating a wetting slag.

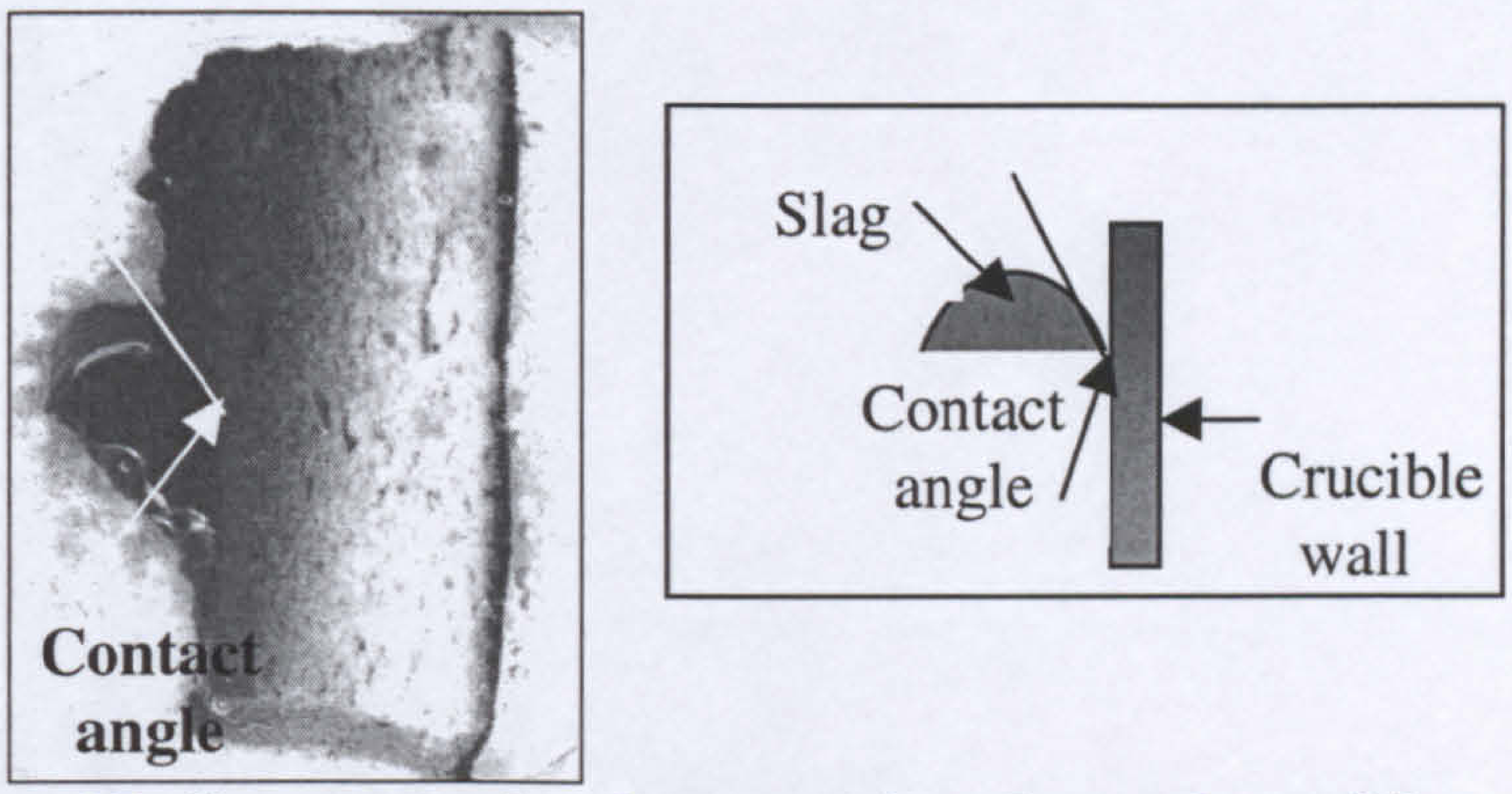


Figure 37: Contact angle of non-wetting slag and crucible wall.

Two pieces of slag, one "bottle" green and one dull blue, were analysed using x-ray diffraction to determine if any microscopic crystals were present in the glassy matrix. The result was negative. Refiring of the slag indicated softening at *c.* 1250^{O}C (Merkel *et al.,* 1995, 12-14).

Polished sections were examined using reflected light microscopy, backscattered electron imaging, and electron probe microanalysis. They revealed metallic spheroidal inclusions that varied in quantity and size. Metallographic and elemental analyses identified these as prills of steel and occasionally cast iron (see *Iron and Steel* below).

The elemental composition of the slag was determined by EPMA using 20 KV, over a 900 μm^2 area, avoiding large metallic prills. A total of twenty-four pieces of slag were analysed. Ten samples were taken from slag still adhering to the crucible wall and fourteen were loose samples from the crucible pit. Twenty-one samples have a similar composition but can be subdivided into a group of seven and fourteen based on their chemical composition, a high manganese group and a low manganese group (Table 4 and Appendix E).

Table 4 : Summary of Elemental Composition of Crucible Slag

High Manganese low K, low Ca Group (7 samples)									
SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	**MnO**	TiO_2	Total
49%	15%	3%	14%	0.2%	2%	1.7%	**12%**	0.5%	97%
Low Manganese Group (14 samples)									
SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	**MnO**	TiO_2	Total
50%	16%	4%	18%	0.2%	3%	1.3%	**2%**	0.5%	95%
Three odd samples									
Sample 34									
SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	MnO	TiO_2	Total
56%	19%	4%	4.7%	0.2%	0.8%	7%	2%	0.4%	94%
Sample 8									
SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	MnO	TiO_2	Total
38%	17%	3%	13%	0.3%	2%	3%	3%	0.5%	80%
Sample 241 (failed crucible)									
SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	MnO	TiO_2	Total
48%	18%	5%	13%	0.1%	2%	11%	0.03%	0.4%	99%

Other elements analysed for but not found in detectable quantities include Ni, Cu, Zn, V, S. P and Ba.

The average elemental composition of the majority of crucible slag is as follows: SiO_2 average 50% (range 45- 53%), Al_2O_3 16% (range 13-18%), FeO 1.5% (range 0.2-2.4), Ca 16% (range 9-21%), K_2O 3.5% (range 2-6.4%), MgO 2.8% (range 1.4 - 4.2 %), Na_2O 0.2%, TiO_2 0.5%, but with a noticeable difference of Manganese: low MnO 2% (range 0.1 - 4%) high MnO 12% (9 -17%). The cause of the low total of sample 8 was not investigated.

The crucible slag contains the non-metallic material remaining from the crucible charge. There does not appear to be any straightforward correlation between the ratios of specific elements, which could suggest that the elements were added together as the components of a particular mineral, except the possible deliberate addition of a manganese rich substance. The slag is homogeneous within a given sample indicating a long enough firing at a high enough temperature to homogenize the slag. The function of the crucible slag would have been to provide a layer to prevent oxidation. Verhoeven noted that the presence of slag was not a necessary aspect of the crucible steel process, however, those ingots that did not have a slag covering, cracked during forging (Verhoeven, pers. com.), thus a coating of slag was beneficial to the process.

Ore, Heat-exposed ore and Smithing Hearth Bottoms

Lumps of a heavy black-brown material were found on the surface in three locations adjacent to thc crucible steel site (see Map 5. 7.F.C, 7.E.II.J and 8.F.IV.E). Pieces that visually appeared to be of a similar material were also found in the crucible steel pit during the surface scrape, two of which werc analyscd (3153F, 3153K). The lumps varied in surface appearance and apparent weight/density when held. Some pieces had a shiny or smooth surface on one side while the other side was uneven and rough, while other pieces had this surface on all sides. Many of these lumps were attracted to a magnet and some showed differences in the strength of magnetism, one side of the lump exhibiting a stronger magnetic attraction than the other. Their magnetic quality and close proximity to the crucible steel sitc suggested that they might be related to crucible steel production. Their identity, however, is not conclusive.

The finds were examined using reflected light microscopy and EPMA to study the elemental composition of the phases. Analyses were performed on selected spots using 25 KV (Appendix F). Many of the phases analysed were quite small, being only a few microns in size. Although care was taken to choose spots that were in the centre of larger phases, areas around the phase may have also contributed to the elemental composition. The purpose of the investigation was to assess whether or not the lumps were related to the crucible steel process, and not details about the genesis. Methods to determine the mineralogy of the phases, such as thin-section analyses or X-ray diffraction were not undertaken.

Ore

Sample ID 161 is identified as an ore. It weighs 56.1 gm and was not magnetic. The sample appears to have three major phases, when viewed using backscattered imaging and in reflected light. The phases are intertwined or sometimes layered and appear to flow in different directions in various areas of the sample (Figure 38). There is no evidence of deliberate heat treatment such as localized vitrification.

Figure 38: ID 161 (7.F.II.F) top (left) and reverse (right).

The first phase appears in reflected light as patchy dark black-brown areas and as bright globules in the backscatter image (Figure 40 point A). Elemental analyses revealed that these bright globules are composed of FeO (86%) with a small amount of calcium (6.5%). The second phase appears as reddish streaks and globules under reflected light and mid grey in the backscatter image (Figure 40 point B). The reddish colour suggested a high iron content, which was confirmed by the elemental analysis of FeO 70% and may be goethite (Rehren, pers. com.). The third phase appears as irregularly shaped fissures that occasionally appear elongated and more spherical areas that are filled with a white material under reflected light and dark in the backscattered image (Figure 42 point C). It is composed of 50% SO_2 and 47% CaO.

The conclusion is that this is an iron ore. The high iron content would make it a good quality ore and the high calcium content would help make a self-fluxing slag. This would have produced a slag with a low viscosity because of the low percentage of Al_2O_3. The alternating iron layers with calcium rich fissures suggest that the lump is a skarn. Depending on the nature of the initial rock and the fluids leading to the metasomatic mineralisation, skarns can form a range of rich ore deposits, particularly for iron or copper (Rehren, pers. com.).

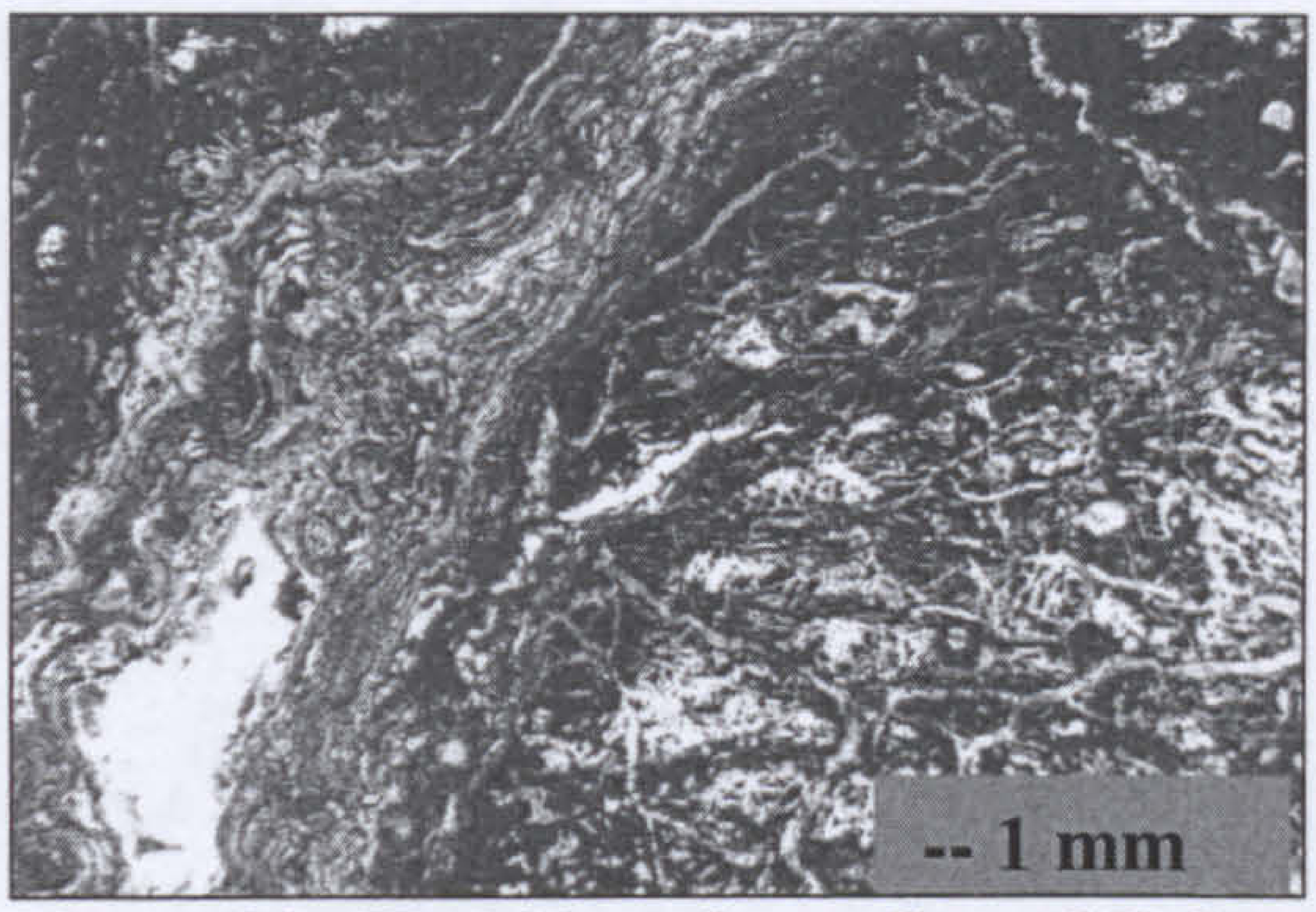


Figure 39: ID 161 under reflected light

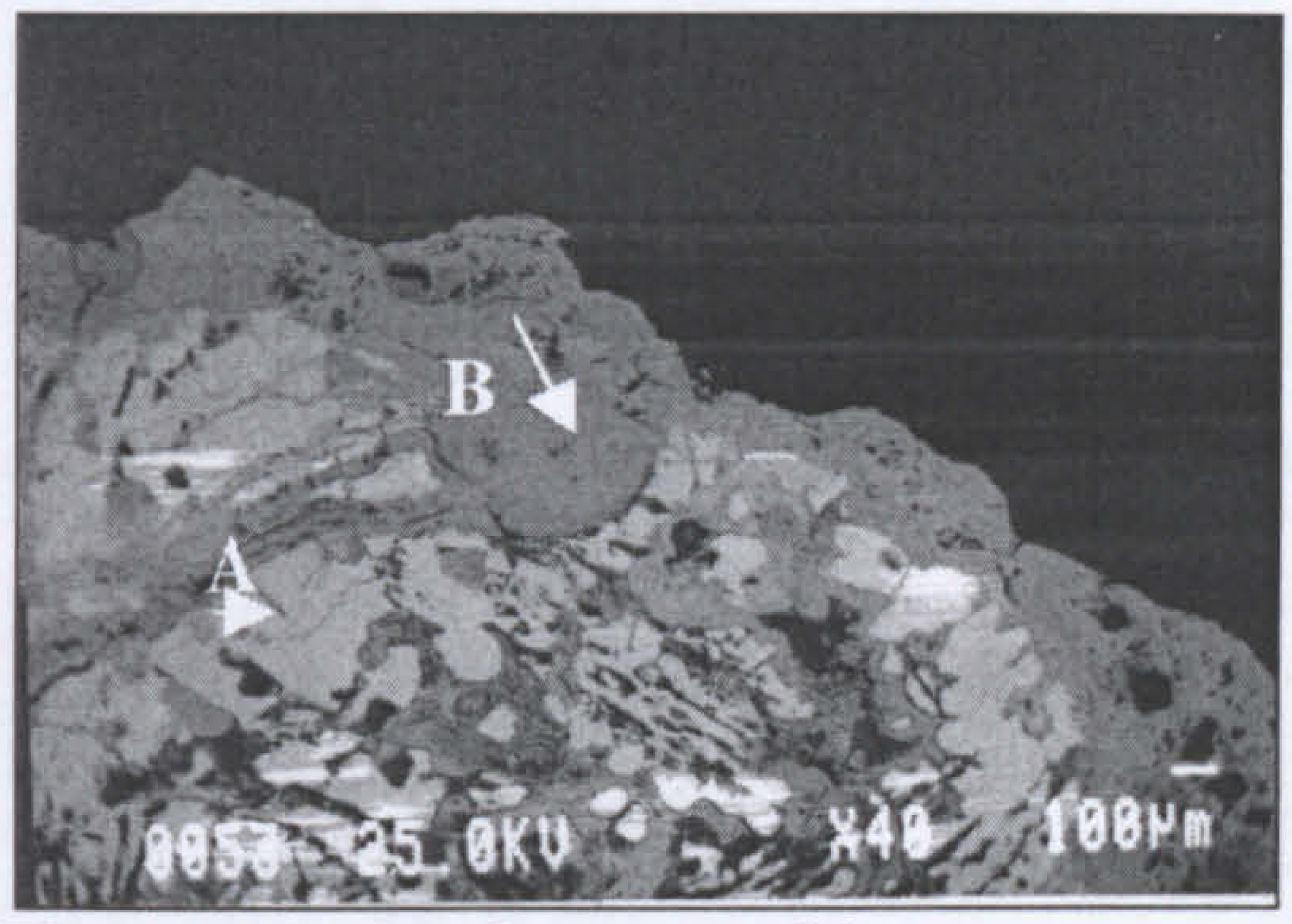
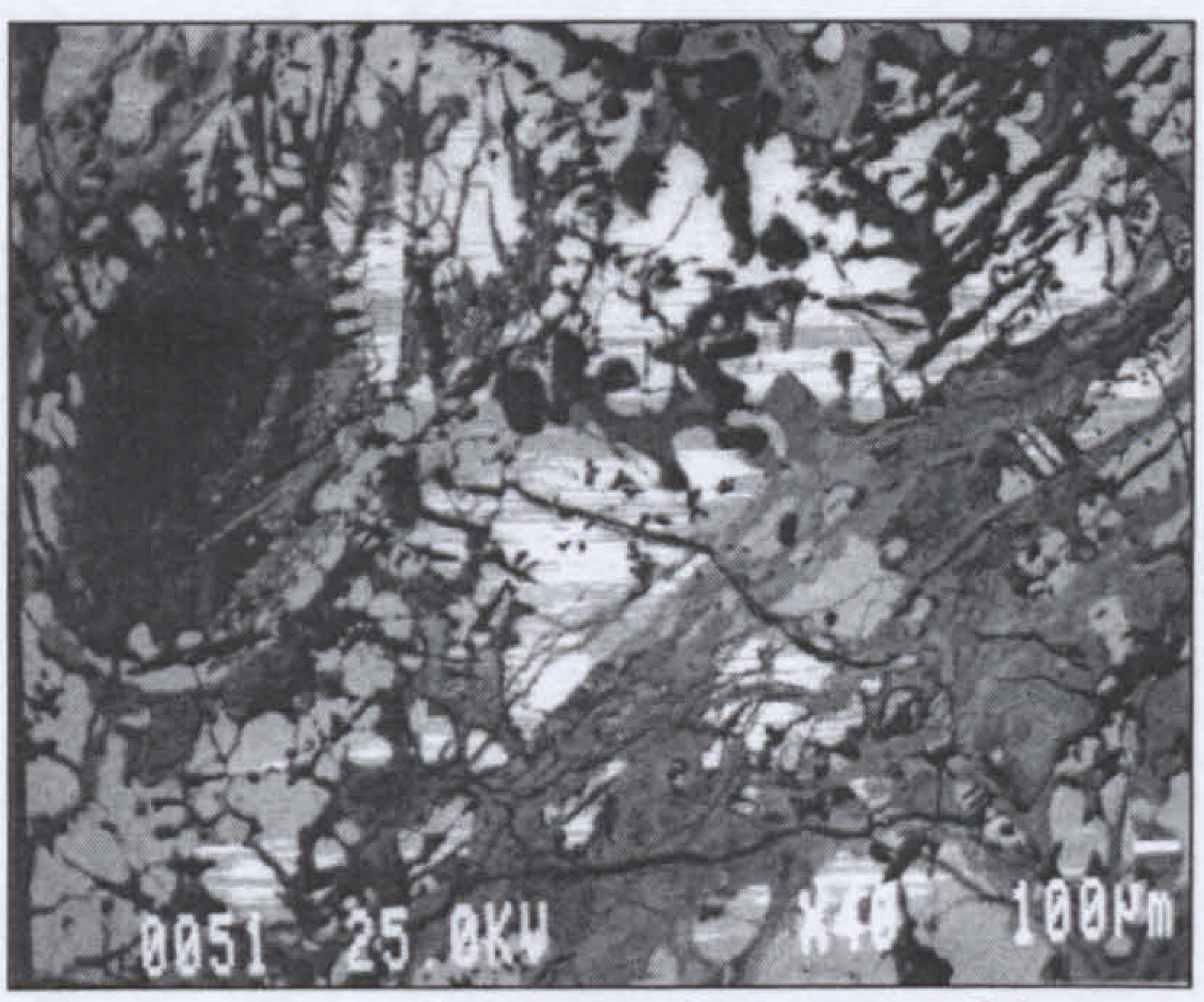


Figure 40: Backscattered image



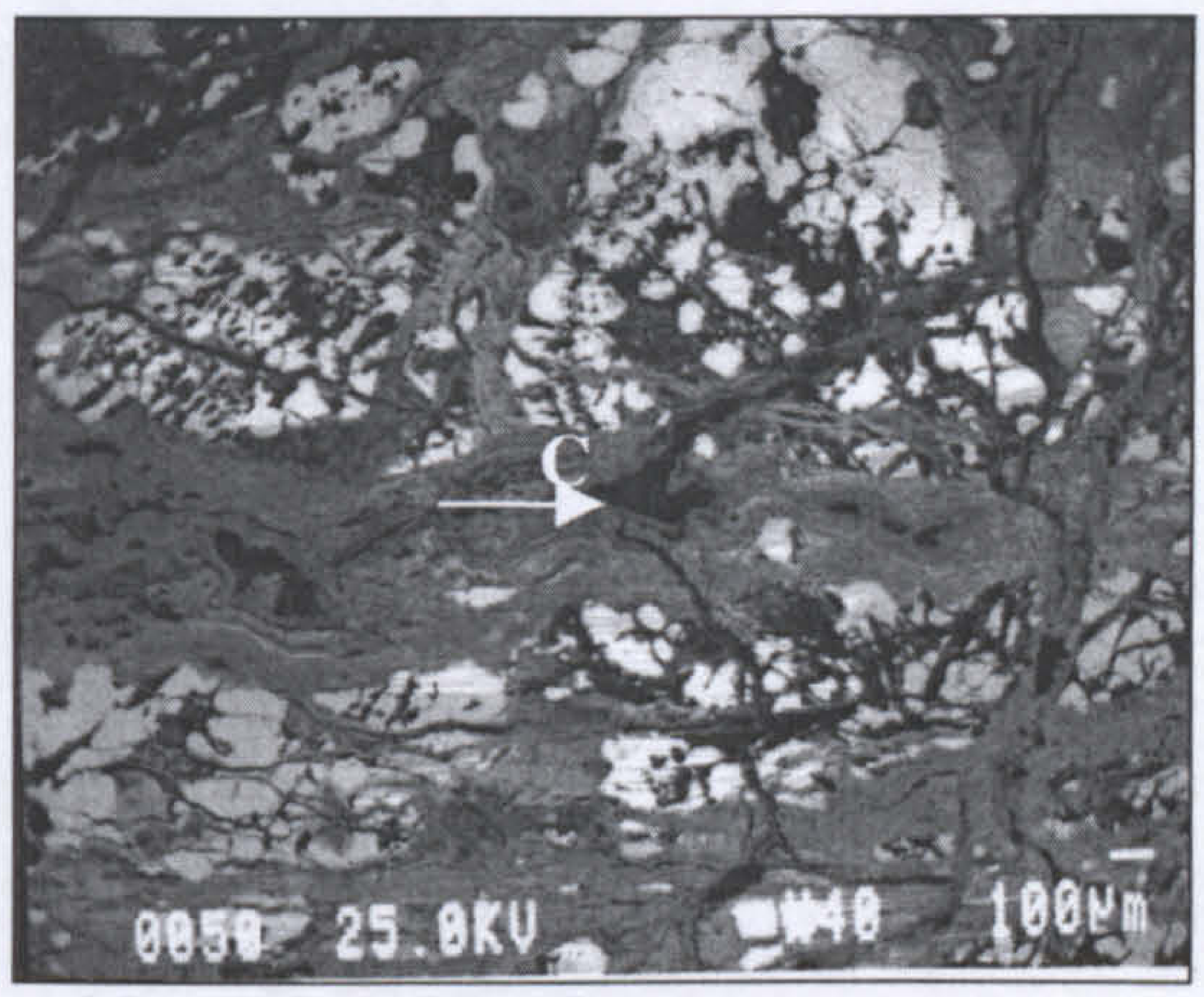


Figure 41 and 42: Backscattered images and location of analyses.

Table 5: Summary of Elemental Composition of ID 161

	FeO	**SiO_2**	**CaO**	**SO_3**	**MnO**	**X**	**Total**
Bright area (A)	**88%**	0	**6.5%**	0	0.7%	0.8%	96%
Mid Grey (B)	**72%**	0	0.2%	0.3%	0	0.5%	73%
Dark Area (C)	0.4%	0	**47%**	**51%**	0	0.6%	99%

X= other elements analyses for (see Appendix F)

Heat exposed Ore

Samples ID #'s 46, 149, 150, 3153 F, and 3153 K are identified as heat exposed ores. The lump ID #46 was collected from a small area to the northwest, adjacent to the crucible steel site, associated with other pieces of magnetic slag, vitrified mud and iron. It weighs 5.6 gm. It was selected for analysis because it was primarily composed of a black magnetic material, with some green vitrified material attached to one side (Figure 43).

Figure 43: ID 46 (7.E.II.J) front and reverse.

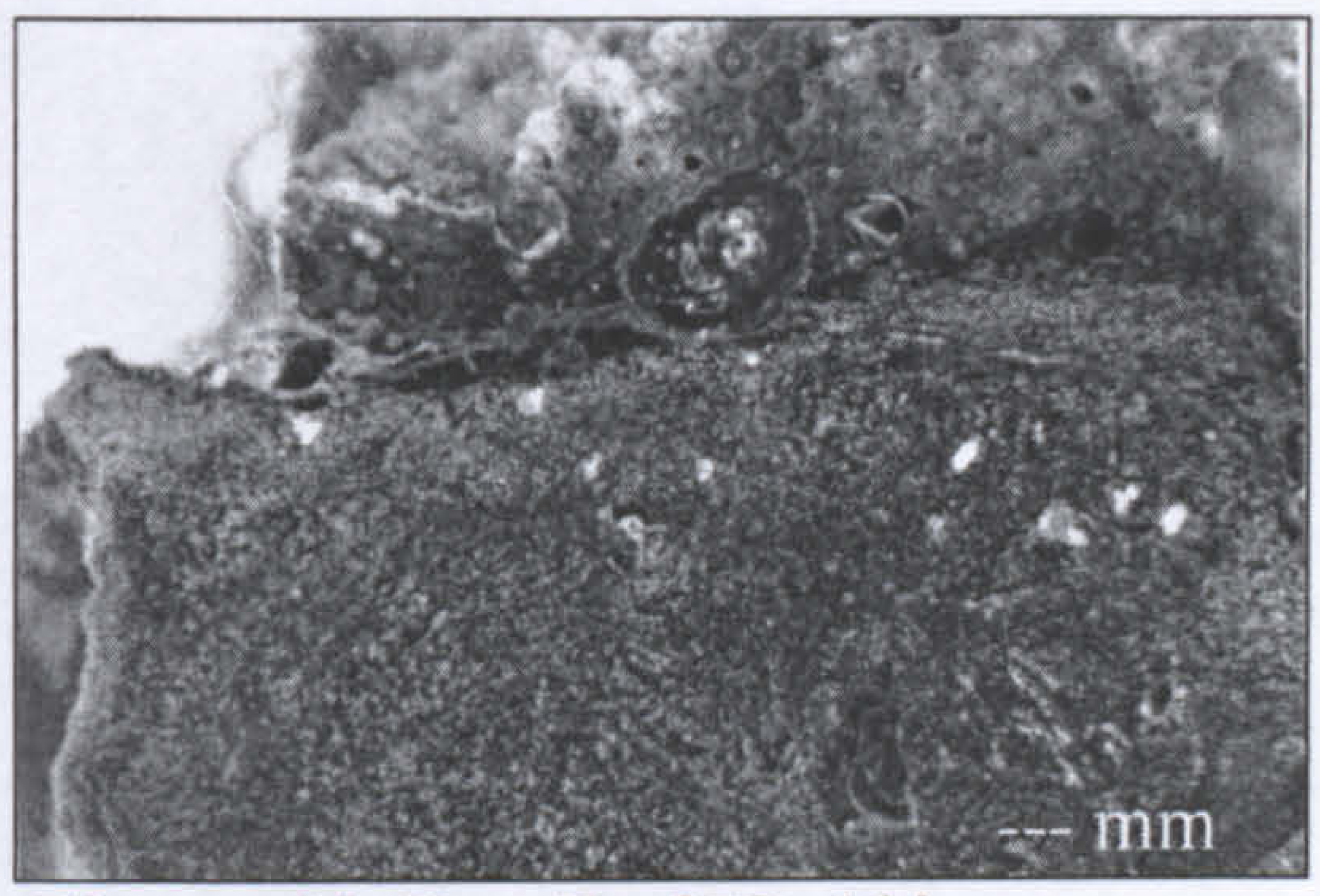


Figure 44: Detail of ID 46 in cross-section.

Under reflected light the sample exhibits a green porous and vitrified material on one side (Figure 44). The rest of the sample has a grey mottled texture and occasional roughly spherical inclusions. The mottled texture has two different reflective properties. Some areas are shinier than others and these areas have no preferred orientation. Under backscattered imaging the sample reflects a variety of phases (Figure 45).

The light grey areas seen in the backscattered image (Figure 45, point A) are globular and composed primarily of iron oxide (85%). Somewhat large irregular shaped dark spots (Figure 45 point B) have 38% CaO, 17% SO_3 and 6.6% Al_2O_3. The elongated mid grey phases (Figure 45 point C) are composed primarily of CaO (62%) and SiO (32%). Grey area (Figure 45 point D) contained 55% SiO_2, 12% CaO, 11% FeO, 10% Al_2O_3, and 3% K_2O. The comparatively high percentage of Al_2O_3 and K_2O, along with the glassy and porous appearance indicates that it is partly vitrified mud brick. The edge (Figure 45 point E) has a porous and vitrified structure. It was primarily composed of SiO2 (47%), CaO (20%), 8.6% Al_2O_3, 7.6% FeO, 4% MgO, 1.5% K_2O.

Its vitrified structure and the presence of Al_2O_3 of other elements suggests that it is completely vitrified mud. The attached vitrified material, the variety of phases, and the high iron content suggests that the lump was heated and is associated with the smelting process.

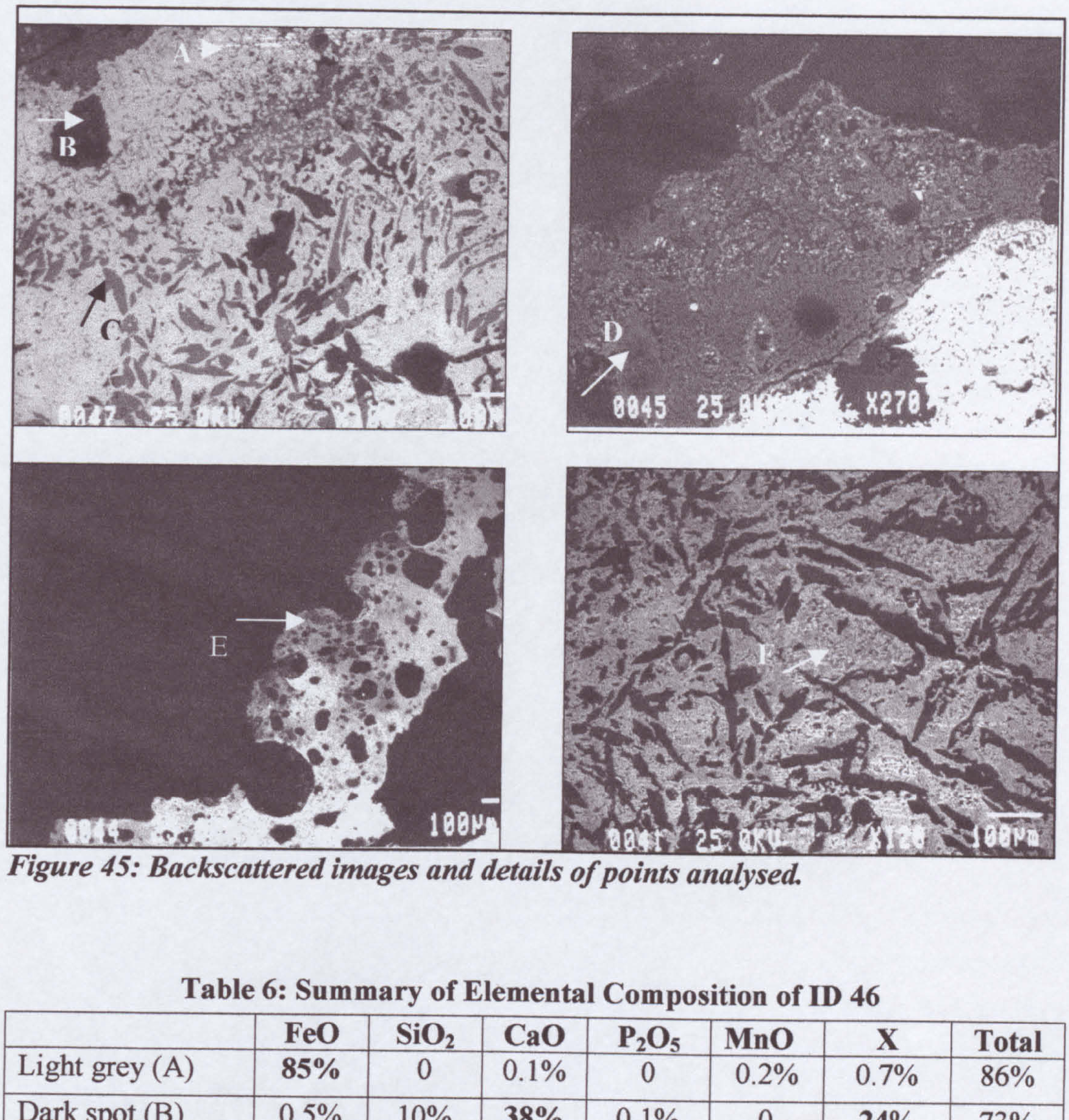


Figure 45: Backscattered images and details of points analysed.

Table 6: Summary of Elemental Composition of ID 46

	FeO	SiO_2	CaO	P_2O_5	MnO	X	Total
Light grey (A)	**85%**	0	0.1%	0	0.2%	0.7%	86%
Dark spot (B)	0.5%	10%	**38%**	0.1%	0	**24%**	73%
Medium Grey (C)	1.3%	**32%**	**62%**	1%	0	0.7%	97%
Grey area (D)	**12%**	**55%**	**12%**	1%	0	**16%**	96%
Edge (E)	7.6%	**47%**	**20%**	0.7%	0.1%	**16.6%**	92%
Centre (F)	**84%**	0	0.5%	0	0.2%	1.3%	86%

X= other elements analyses for (see Appendix F).

The lump ID # 49 (Figure 46) was found in the same area as the lump examined above. It is primarily black with brownish areas and white inclusions. It is magnetic and weighed 124.8 grams. One side is comparatively flat and compact whereas the other side is slightly convex and porous.

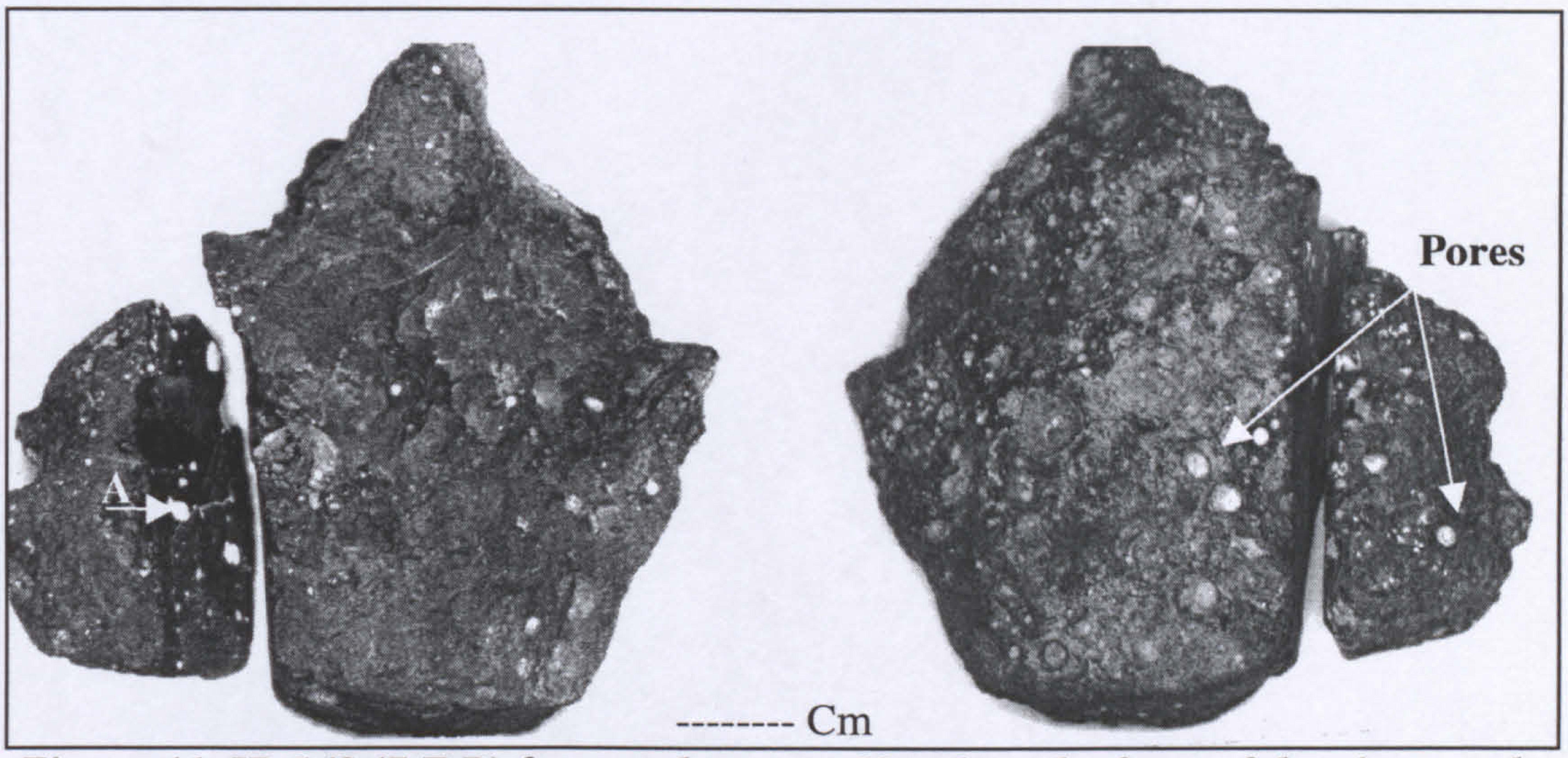
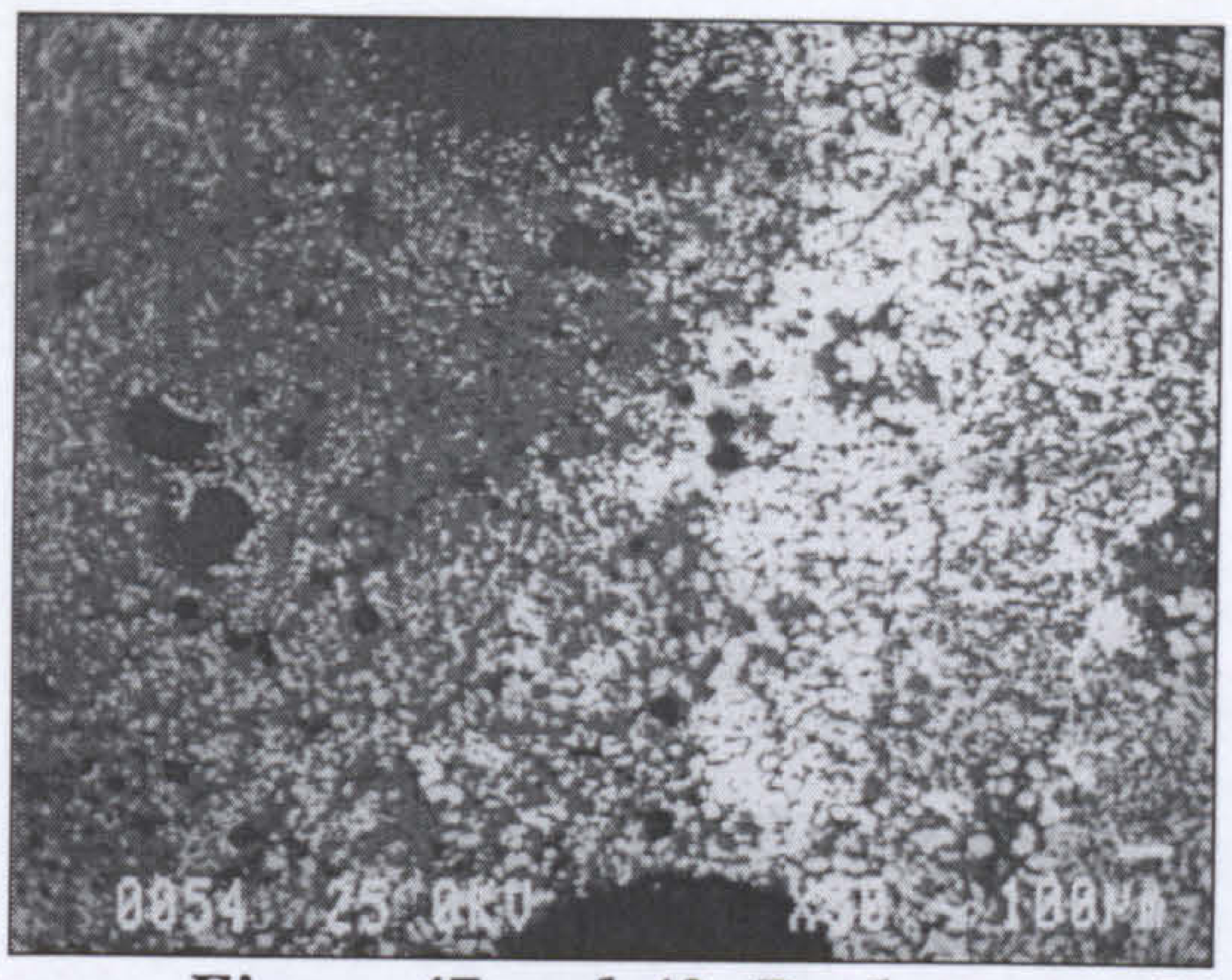


Figure 46: ID 149 (7.F.B) front and reverse. Note how the front of the piece on the left is relatively flat and compact, whereas the reverse (right) has pores.

The cut section of the lump revealed circular areas containing a white material, which often fills associated fissures (Figure 46, point A). These white areas appear black in the backscattered images (Figure 47 and 48). The backscattered image of the polished section revealed three different areas, dark grey and light grey areas in addition to black inclusions. The elemental composition of these black areas revealed that they were high in calcium (64%) and the low total is probably due to the presence of carbon and oxygen, thus the inclusion is probably a form of calcium carbonate. Apparently the calcium carbonate has become deposited in the pores and in the fissures, and is probably a product of a secondary process such as weathering. The dark grey areas have an irregular appearance; some of them have comparatively straight sides. They are composed of around 64% CaO and 32% SiO_2. The light areas are globular and are primarily composed of FeO (86%) and MgO (3.4%).



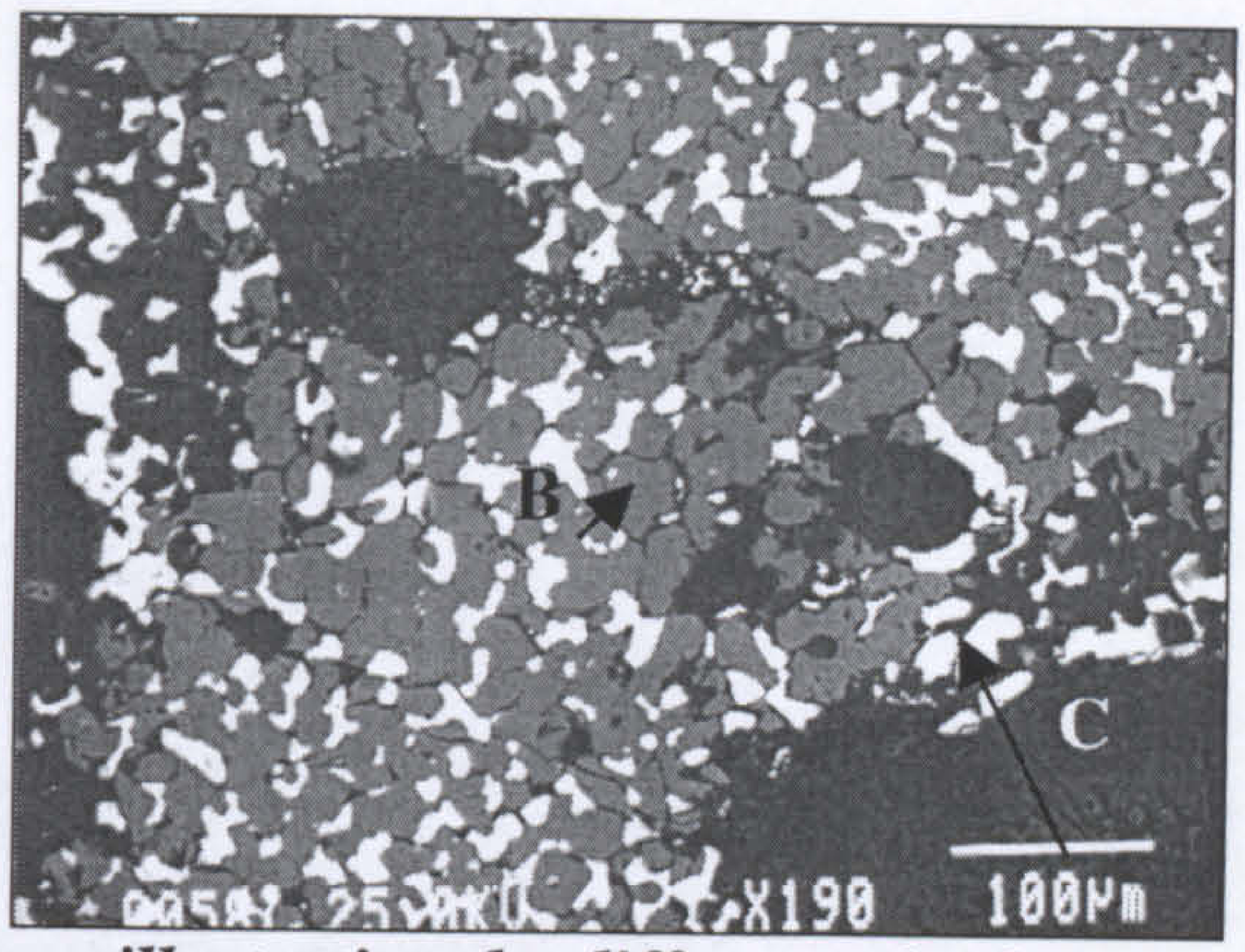


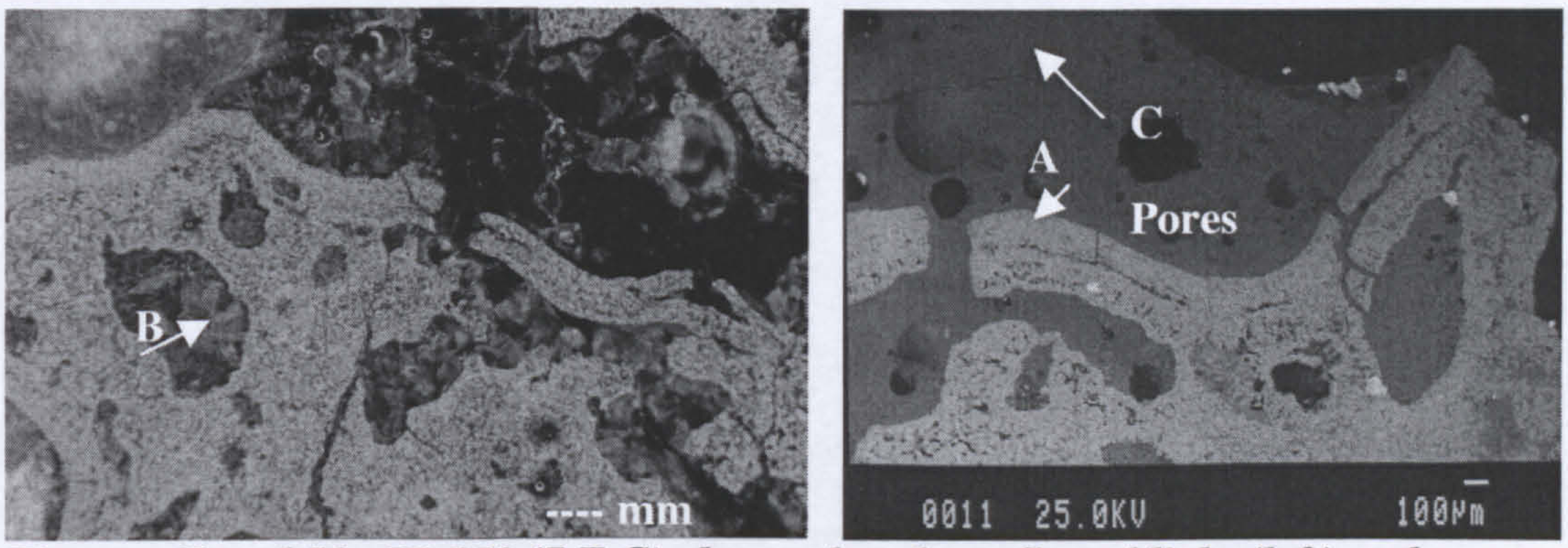
Figure 47 and 48: Backscattered images illustrating the difference in the concentration of the lighter phases toward the left side of Figure 41.

Table 7: Summary of Elemental composition of ID 149

	FeO	**SiO_2**	**CaO**	**MgO**	**P_2O_5**	**X**	**Total**
White areas (A)	0.4%	0	**64%**	0.3%	0.1%	0.2%	65%
Dark Grey areas (B)	1%	**32%**	**64%**	0.1%	0.9%	1%	99%
Light Grey areas (C)	**86%**	0	0.6%	**3.4%**	0	1%	91%

X= other elements analyses for (see Appendix F)

Lump ID 150 was one of at least a dozen lumps of varying sizes found on the surface in the area within the grid reference 7.F (see Map 5). The crucible steel workshop was found in quadrant II of 7.F and therefore the remains were assumed to be associated with the crucible steel workshop. The lump is strongly magnetic and weighs 51.6 gm. It was chosen for analysis because it had fired mud and a greenish smooth glassy material over an uneven surface on one side, while the other side was black and exhibited extensive pores and vesicles (Figures 49 and 50). The fracture is metallic and shiny. The lump was partly liquid, indicated by the glassy material, pores, vesicles and the undulating appearance of the light grey structures within the glassy material.



Figures 49 and 50*: *ID 150 (7.F.C) observed under reflected light (left) and backscattered electron imaging (right). The labels correspond to the analyses in Table 8.

The reflected light photomicrograph and the backscattered image are not of the same area but were adjacent to each other and show similar features. Microscopic analysis revealed two major phases, one light grey in both images and one black and glassy. The latter phase under reflected light containing greenish crystalline structures; whereas in backscattered imaging these appear medium grey. The circular dark grey/black areas are pores but the few bright spots in figure 50 are surface contamination. Under microscopic examination the light grey phases are generally globular. The elemental analyses indicated that this area was mainly composed of iron oxide around 80%.

Under reflected light and in the backscattered image the glassy material is beginning to crystallize (Figure 49 point B). The glassy green material is both visually and elementally similar to the green glassy slag found inside the crucibles. The glassy material of sample ID 150 contains a similar amount of SiO_2, CaO, and K_2O to the crucible slag; over 45% SiO_2, 16% CaO, and around 3% K_2O (see above and Appendix F). The glassy material has more FeO, between 4% and 21%, than the crucible slag at around 1.5%. The crucible slag also has a slightly higher percentage of Al_2O_3, 16%, compared to around 10% in the glassy material.

The average of the three major elements in the glassy material inside the sample normalized is 65% SiO_2, 19% CaO, 16% Al_2O_3. Plotted on the silica-alumina-lime compositional triangle gives a melting temperature of 1440 ^{O}C (Rostoker and Bronson, 1990, 198). However the presence of K_2O, Na_2O and FeO, totalling around 10% of the total composition of the glassy material, would have lowered the melting temperature considerably.

The lump appears to be iron smelting slag where the slag has for the most part separated from the iron oxide and has rose to the surface. The high percentage of CaO at first seems peculiar because CaO, over about 6% and typically less, is not recorded in traditional bloomery slag (see Rostoker and Bronson, 1990, 91 table 9.1a and 9.1b). The higher percentage of iron oxide virtually eliminates the possibility that this slag is from the production of cast/pig iron because cast/pig iron typically contains less than 5% iron oxide (see Rostoker and Bronson 1990, 105). The CaO was primarily from the ore (see below).

Table 8: Summary of elemental Composition of ID 150

	FeO	SiO_2	CaO	Al_2O_3	MgO	X	Total
Light grey (A)	**82%**	1%	2%	0.3%	0	0.7%	86%
Green/Grey (B)	**16%**	**42%**	**17%**	8.4%	2.1%	5.5%	91%
Glassy top (C)	5.6%	**51%**	18%	12%	0.2%	8.2%	95%

X= other elements analyses for (see Appendix F).

This small piece, ID #3153 F, was found in the crucible pit. It is black with a smooth texture on one side and a comparatively rough texture on the other (Figure 51). It is relatively heavy for its size but is not magnetic. Small pores, around 1 mm in diameter is observed on all sides and in the cross-section. The fracture is metallic with a silvery reflection. The smooth top may be the result of flowing during solidification, but it may also be the natural cleavage. The small size of the piece and the rough, jagged edges suggest that the piece was deliberately broken.

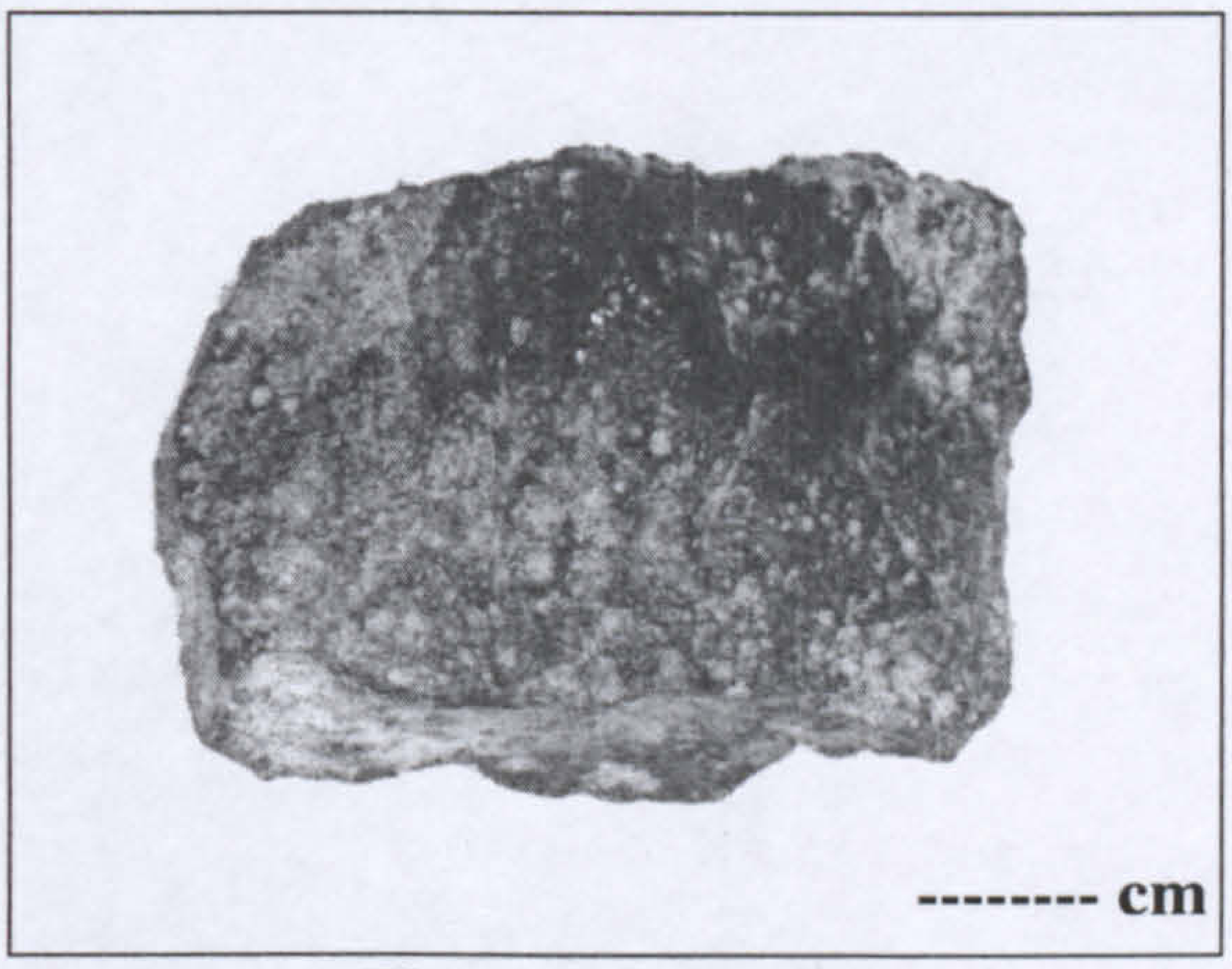


Figure 51: 3513 F

Examination of the cross-section using backscattered imaging revealed a relatively homogenous material consisting of three phases, a round dark grey phase (Figure 52 point A), a light grey globular phase (Figure 52 points B and C), and a medium grey glassy phase (Figure 52 point D) filling in the areas between the light grey phase. The dark grey phase has a high percentage of CaO (28%) and MgO (6%). This phase appears white under reflected light. The light grey phases are probably wüstite as they contain around 90% FeO. The presence of calcium is probably from the inadvertent analysis of the surrounding area due to the small size of the phase. The medium grey phase (Figure 52 phase D) is glass composed primarily of SiO_2 (32%) and CaO (64%).

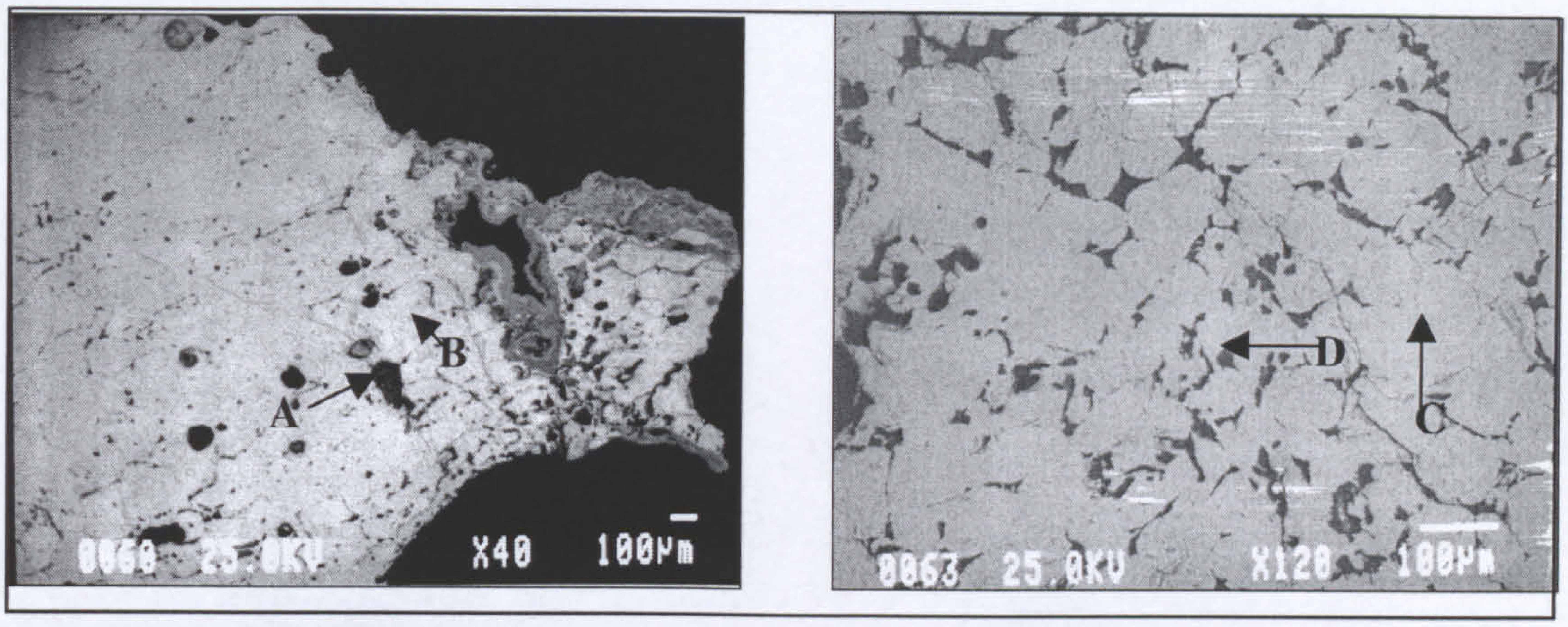


Figure 52: 3513 F Backscattered images and detail of points.

Table 9: Summary of Elemental Composition of ID 3153F

	FeO	SiO_2	CaO	MgO	MnO	Al_2O_3	SO_2	X	Total
Dark Grey phase (A)	2%	0.6%	**28%**	**6%**	0	0	0.2%	1.2%	38%
Light Grey phase (B)	**93%**	0	1.5%	1%	0.5%	0.2%	0	0	96%
Light Grey phase (C)	**89%**	0	**3%**	1%	0.3%	0.3%	0	0.4%	94%
Medium Grey phase (D)	1.6%	**32%**	**64%**	0	0	0	0	1.4%	99%

X= other elements analyses for (see Appendix F).

Lump, ID # 3153 K was also found in the crucible pit. It is not metallic. In the cross-section it is obvious that the piece is highly inhomogeneous. One side has white fissures in a primarily reddish matrix where as this suddenly changes to a comparatively homogenous black matrix, with no white fissures or other features obvious to the naked eye (Figure 53). The arrows next to the backscattered images (Figure 54) indicate the location of the area in relation to the other areas.

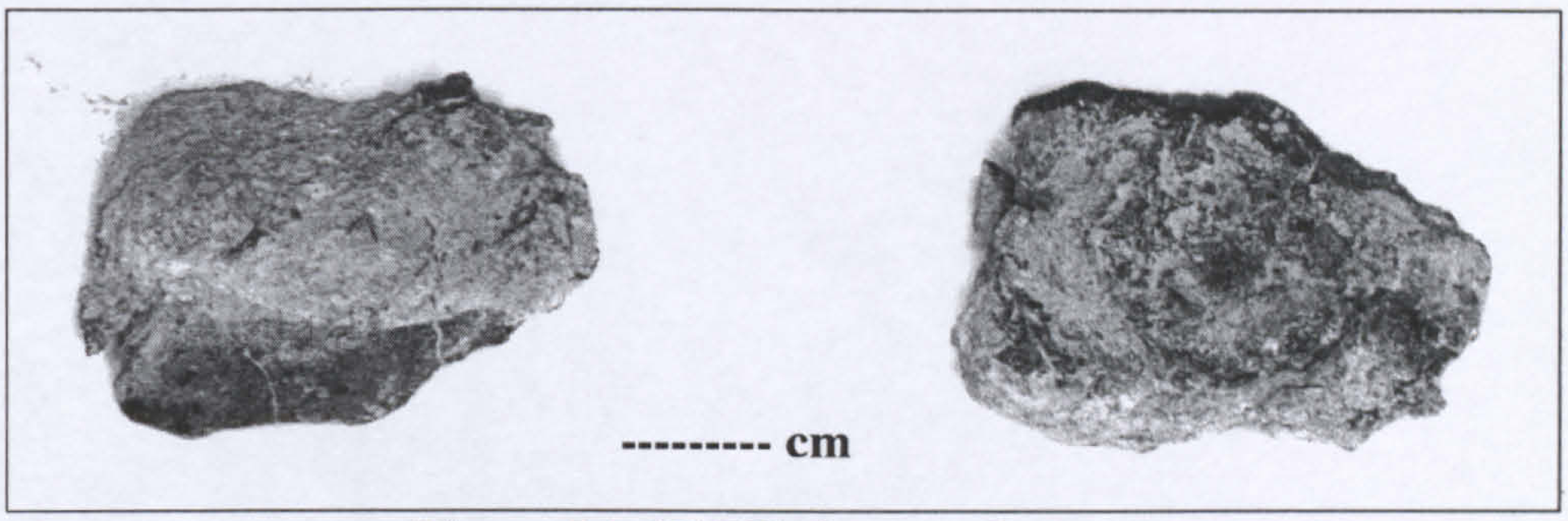


Figure 54: 3153K, front and reverse.

Using backscattered imaging, the black matrix had five visually distinct phases (Figure 54 points A-E). Point A is observed as dark crystals that generally have four straight sides. These crystals are primarily composed of SiO_2 31 %, Al_2O_3 17%, CaO 39%, and MgO 2.1%. To the right of the area where these crystals are concentrated, is an area of bright dendrites, point B. The dendrites are composed of around 89% FeO and 1.5 % MgO, 2% MnO and are identified as wüstite. Point C has a mottled appearance consisting of small bright globular areas in a glassy matrix. The analysis concluded that these are small areas of wüstite. Point D appear as dark holes in backscattered images and white under reflected light, the largest of which was analysed and found to be composed primarily of CaO 37% and SO_3 21% with a small amount of SiO_2 5 %, and Al_2O_3 5%. The point E, at the edge is glassy. The composition of the glass is 32% SiO_2, 24% CaO, 18% FeO, 12% Al_2O_3, 3.5% MnO, 2% K_2O. The composition is probably due to reactions with the furnace wall (see below).

In Figure 54, (top right image) there are two distinct areas. Near the top of the backscattered image the area has a dark grey matrix with coarse inclusions, below a lighter grey matrix with a fine texture. The dark angular crystal (F) is composed of 52% SiO_2 and 22% Al_2O_3 with smaller amounts of 7% CaO and 4% K_2O. Point G is mid grey the backscatter image and reddish-orange in reflected light and composed primarily of iron oxide, 70% FeO. Point H is light grey angular crystal. It is composed of 78% FeO, 6% CaO and 4% MgO.

Figure 54 (bottom right image) has four distinct phases in the backscattered image. There is a higher concentration of a grey phase (see C) on the left side of the sample whereas black elongated diamond shaped crystals (I), medium grey tetragonal shaped crystals (K), and light grey areas (L) are concentrated to the right. The black crystals (I) have a slight preferred vertical orientation and concentration. They are composed of 48% SiO_2, 29% CaO, and 2.9% P_2O. Above these there is a circular glassy area (J) composed of 48% CaO, 28% FeO, and 19 % Al_2O_3. The medium grey tetragonal crystals (K) are composed of 63% CaO and 32% SiO_2. Point L is light grey angular crystal and is probably the same as point H. The composition is around 80% FeO, 4% CaO, and 5.9 % MgO.

The concentration of unreacted ore on one side that has transformed to wüstite in a glassy matrix on the other side indicates that this is an ore that was exposed to heat more on one side that the other but the smelting process was not compete.

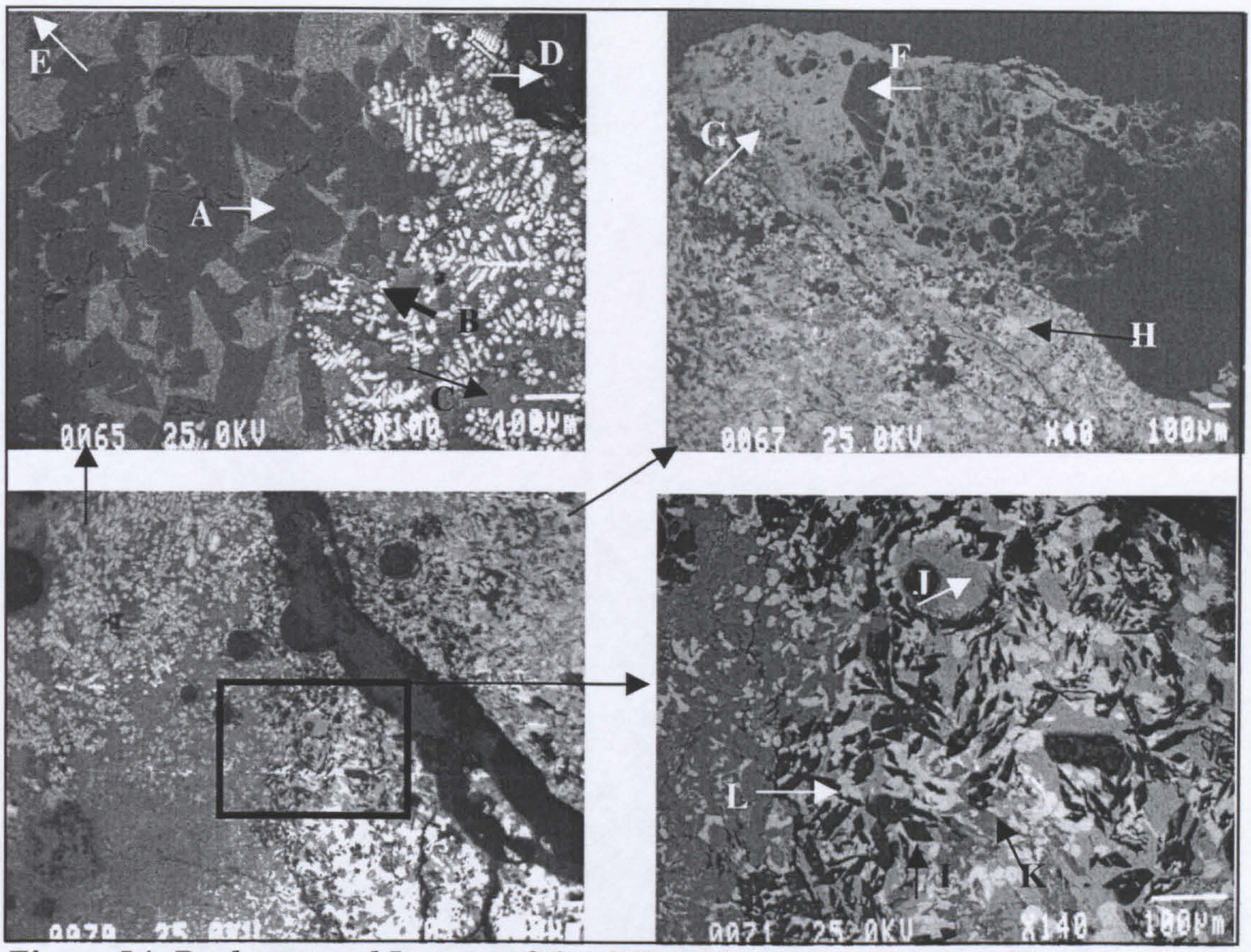


Figure 54: Backscattered Images of the different structures observed in 3153 K.

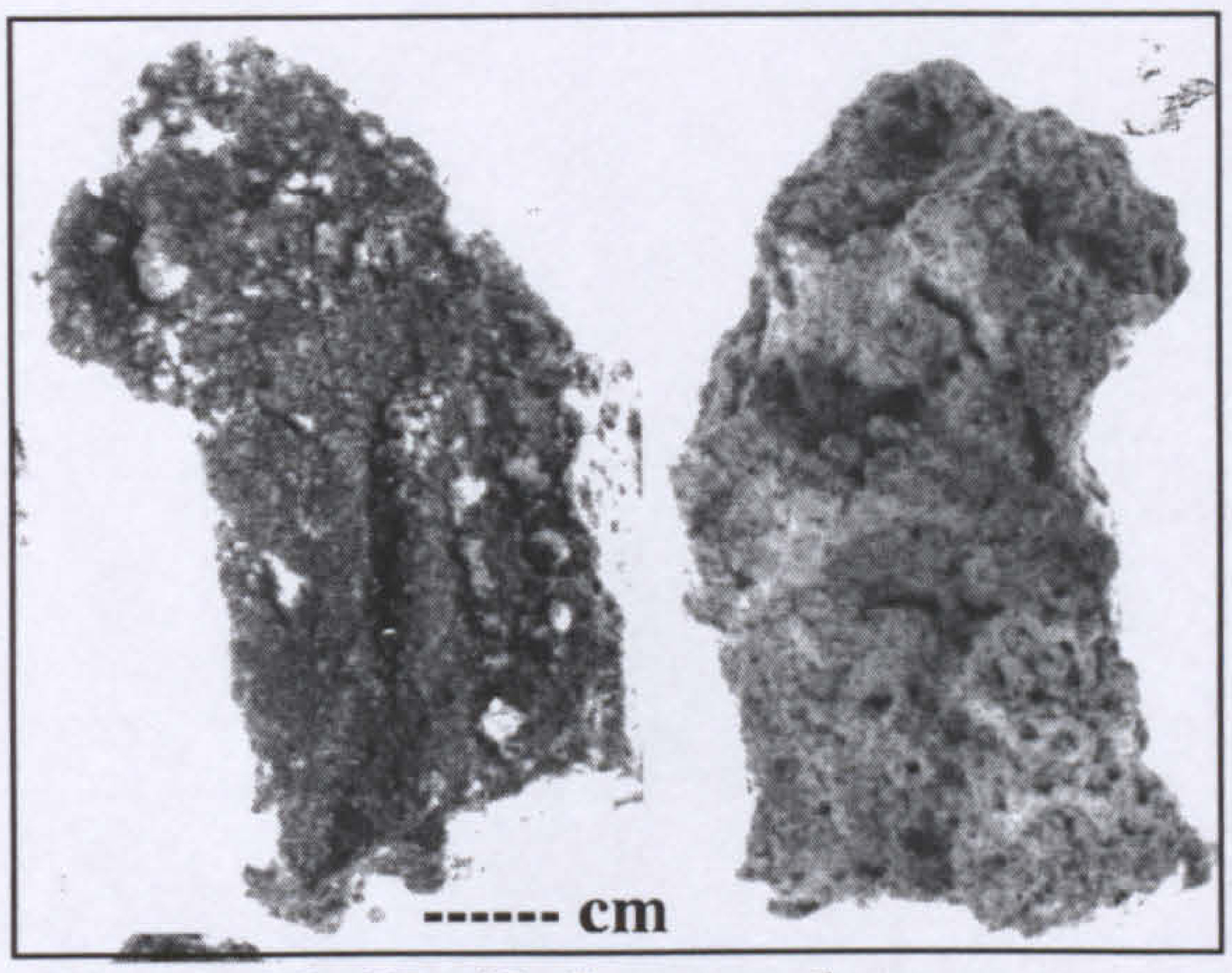
Table 10: Summary of Elemental Composition of ID 3153K

	FeO	SiO2	CaO	MgO	MnO	Al2O3	SO3	X	Total
Angled (A)	4.8%	**31%**	**39%**	**2%**	0.2%	**17%**	0	0	94%
Dendrite (B)	**89%**	0	0.5%	**1.5%**	2%	0.4%	0	0.6%	94%
Mottled (C)	**89%**	0	1%	**2%**	0.7%	0.3%	0	1%	94%
Dark (D)	0.2%	5%	**37%**	0	0	5%	**21%**	0	68%
Edge (E) *not illustrated*	**18%**	**32%**	**24%**	1%	**4%**	**12%**	0.3%	3.7%	95%
Dark angular (F)	0.9%	**52%**	**7%**	1%	0.3%	**22%**	0.9%	2.9%	87%
Mid Grey (G)	**70%**	0%	0.3%	0	0	0	0.3%	0.4%	71%
Light area (H)	**78%**	0	6.5%	**4%**	0.8%	0	0	0.7%	90%
Dark diamond (I)	0.8%	**48%**	**29%**	0	0	0.1%	0.6%	**5.5%**	84%
Circular glassy (J)	**28%**	0	**47%**	0	0	**19%**	0	2%	96%
Medium grey diamond (K)	0.9%	**32%**	**63%**	0	0	0.1%	0	3%	99%
Light grey area (L)	**80%**	0	**4%**	**6%**	0.8%	0	0	0.2%	91%

X= other elements analyses for (see Appendix F).

Smith hearth bottom

The sample, ID # 45, was taken from a 26.5 gm black semi-circular lump, which was not attracted to a magnetic. One side of the lump is relatively smooth while the other is uneven and slightly vesicular (Figure 55). Both sides appear to be the original surface layers, which makes the original lump roughly 9 cm in diameter and 1 cm thick. There are a few small white inclusions and some rusty areas visible in the hand section.



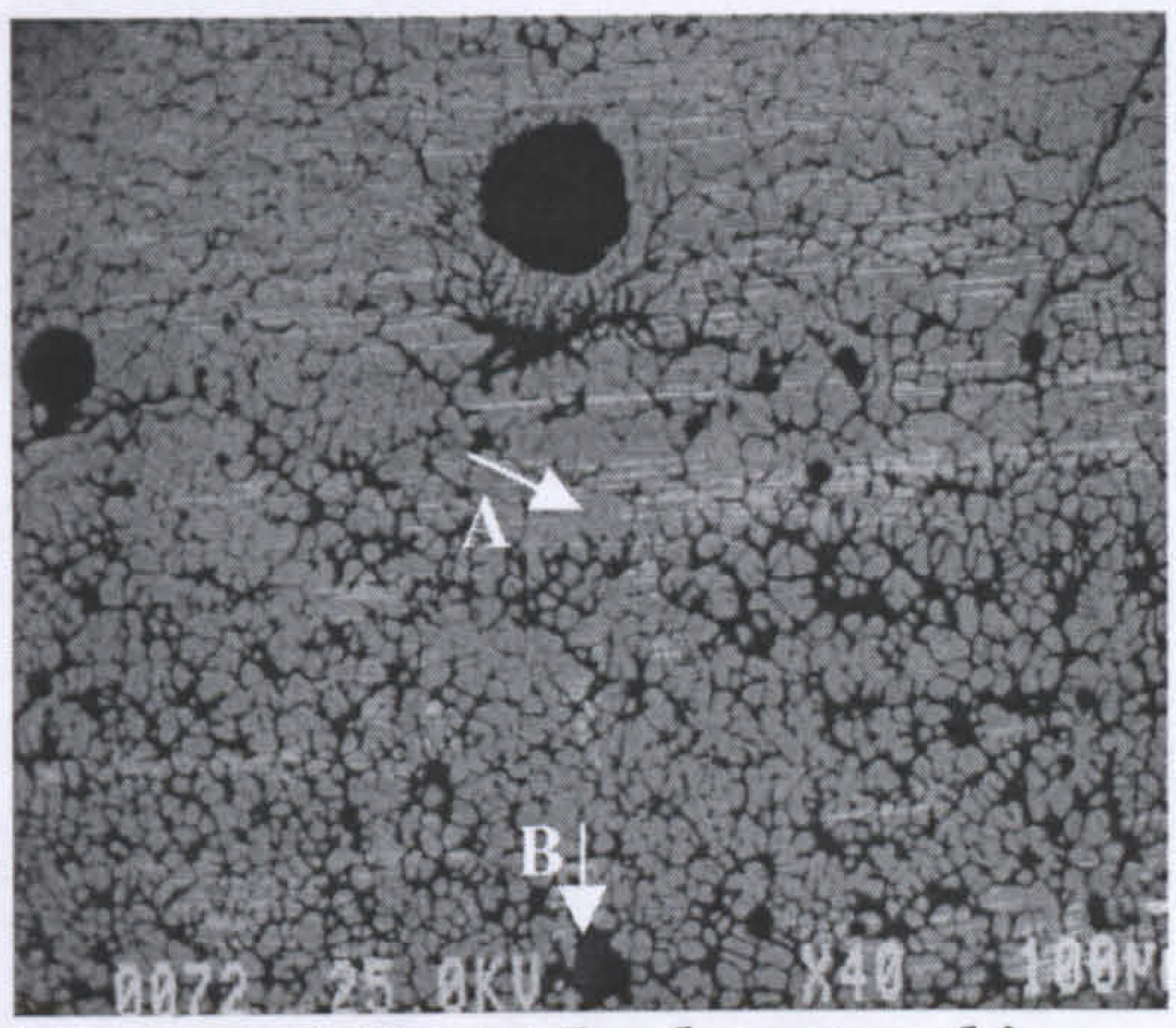


Figure 55: ID 45, front and reverse. ***Figure 56: ID 45 Backscattered image***
The white streaks across figure 56 are from the development of the photograph, not the actual sample.

The globular bright areas, composed primarily of FeO (89%), are wüstite. They have a weak layered structure with larger globular areas concentrating on the lower section of the sample (top of Figure 56). The darker areas in between the wüstite are glass composed of CaO (35%), SiO_2 (31%), and FeO (26%). Other elements include 1.2% MgO and 0.9% P_2O_5. No Al_2O_3 was detected in this phase and only 0.2% Al_2O_3 was found in the bright area. The shape and layered structure suggest that this is probably a piece of a smithing hearth bottom.

Table 11: Summary of Elemental Composition of ID 45

	FeO	**SiO_2**	***CaO***	**P_2O_5**	**MnO**	**X**	**Total**
Bright area (A)	**89%**	0	0.1%	0	0.1%	0.8%	90%
Dark Area (B)	**26%**	**31%**	**35%**	.8%	0.1%	2.1%	95%

X= other elements analyses for (see Appendix F).

Large circular lumps containing iron were found during the excavation (Figure 57). They are probably what the Soviet archaeologists identified as iron blooms but are in actual fact smithing hearth bottoms.

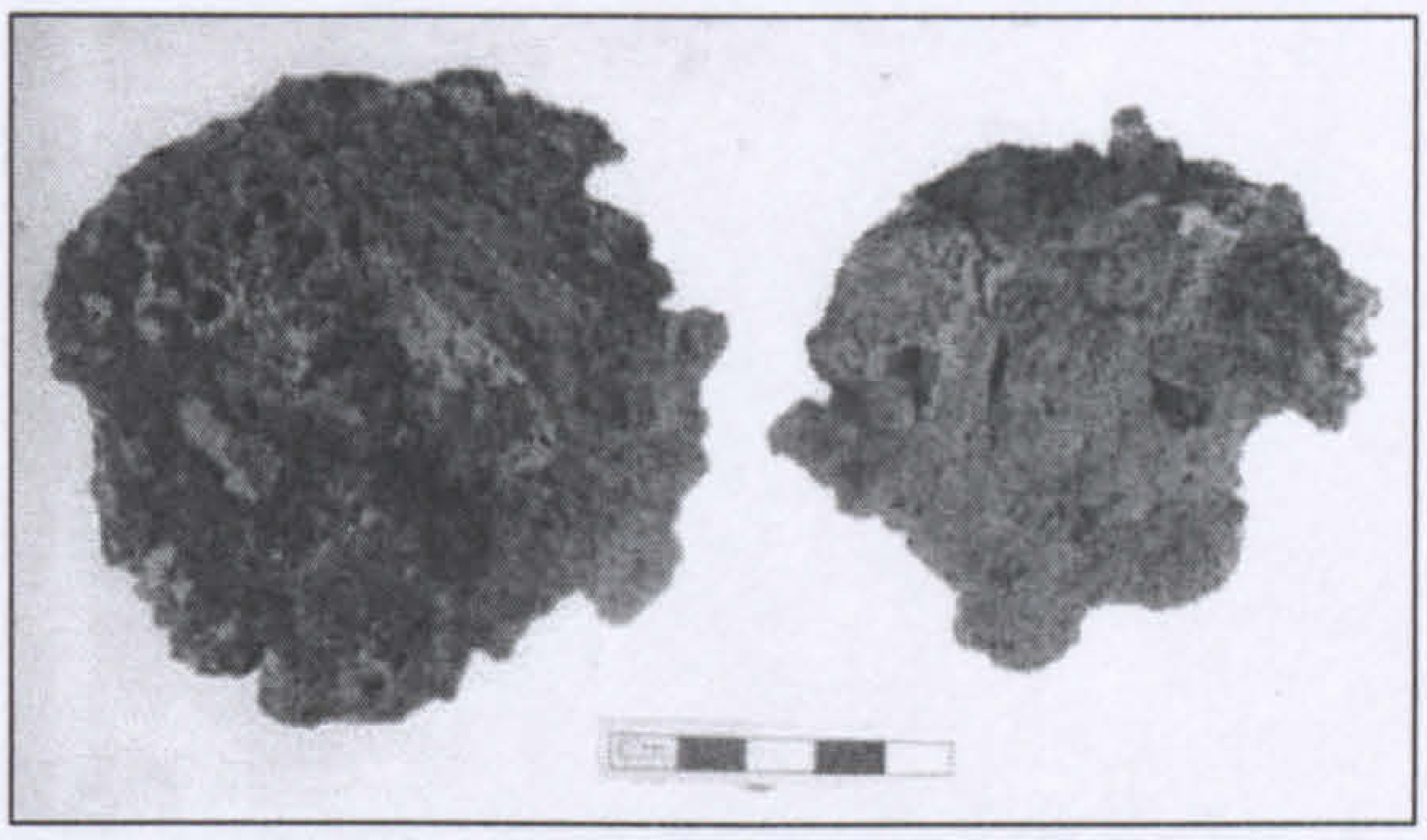


Figure 53: The so-called "Iron blooms" that are actually smithing hearth bottoms.

However, the identification of ore and heat-exposed ore does indicate that Russian archaeologists may have found actual iron blooms, but no evidence for their findings have been published.

The results of the analyses indicated that one lump is iron ore (ID 161), five lumps are pieces of iron ore that were exposed to intense heat (ID 46, ID149, ID150), and one lump is probably a smithing hearth bottom (ID 45). Their identification and relationship to the crucible steel process is not obvious, however their presence around the workshop and their composition suggest that they are somehow related to the process.

The heated ore and smithing hearth bottom have an elemental composition different from most known ancient slags, particularly in the percentage of CaO. Often CaO in the slag is from the fuel ash, but if the iron ore found at the site was used in the smelting process, than at least some of the CaO in the slag was from the gangue in the ore. Russian scholars excavating at Merv interpreted heavy concave-shaped iron-rich lumps as "palm-shaped ingots" (Usmanova pers. com.). Re-examination of these objects, and in light of laboratory research, these "palm-shaped ingots" are smithing hearth bottoms. Their circular and concave shape along with the flat top, porous base and interior, and layered microstructure consisting of wüstite and glass are typical of smithing hearth bottoms. The majority of lumps are iron ores that were exposed to intense heat and have begun to react, rather than true smelting slag. If these were pieces of true slag the original minerals and layers would not still be visible.

As only one piece of ore not exposed to heat was found, it is not possible to know if it was representative of the ore the smelters were using. Indeed it is not conclusive that ore of this type was used in the smelting at all. The overall composition, however, is not inconsistent with the smelting slag found in the same area and it is similar to a piece of partially reacted ore found in the crucible pit (3153 K).

The edges of the pieces of heated ore are quite sharp and look as though an edged implement deliberately broke them when they were cool, thus producing a sharp fractured edge. This is inconsistent with the consolidation of bloomery iron, which is performed by the hammering of the bloom while it is hot, although initial cleaning of the bloom is often done when cool.

One assumes that the smelting slag was originally part of a ferrous bloom probably imported to Merv for the production of iron/steel objects. The resulting question is what role, if any, did slag play in the crucible steel process. If the smelting slag was placed into the crucible along with other crucible charge materials, presumably metallic iron and perhaps a carbonaceous material (see below), the iron oxide and associated metallic elements would have reduced to metal and the remaining elements would gather in the crucible slag. Therefore, one may assume that the slag in the crucible and the associated metal prills would have a corresponding elemental composition as the smelting slag plus the other crucible charge materials after reduction.

Although a piece of iron ore and various pieces of heated ore were found at Merv there is no evidence that smelting was undertaken there. Smelting sites are generally characterised by large quantities of smelting slag and remnants of furnace installations. They are usually situated away from cities, near the ore and where fuel is abundant. Merv has no ores and comparatively little fuel would have been available. In addition the quantity of slag is comparatively low (estimated at less than a dozen kilos total) compared to what would be expected from a smelting site (possibly tons).

It is virtually certain that the piece of iron ore was brought to Merv because Merv is an alluvial deposit consisting of fine silt. According to Allan's study of iron sources according to medieval Islamic texts, the sources closest to Merv are Gūzgān, Kābul, and Wastānāt (1979, 133-135). These regions are in modern day Afghanistan and indeed the geology of Afghanistan supports the argument. The ore may be from the area known as Gūzgān. During the Islamic period the area was said to be rich in iron ores in the Hudud al-Alam (Minorsky, 1937). Gūzgān is the mountainous region of near the Hindu Kush at the end of the Murghab River. The mountains of this region consist of volcanic rocks of tertiary age, an area that is geologically consistent with the formation of skarn. Skarn is often used as an ore because of its reasonably high iron content, or other metals such as copper. The presence of calcite in the skarn acts as a flux creating a low viscosity slag and skarn can be considered a self-fluxing ore. Further evidence for the hypothesis that the ore came from Northern Afghanistan are Islamic remains along the Murghab River in Afghanistan (Ball, 1982) indicating occupation of this area during the Islamic period.

One possible scenario is the smelting of the skarn ore to bloomery iron in the mountains near the iron source. The unconsolidated or partially consolidated bloom would be transported along the Murghab River to Merv where it was sold for the crucible steel process while other blooms were probably used for the production of wrought iron objects.

Iron and Steel

Iron and steel remains were primarily found as two groups: as individual lumps, and as prills associated with the crucibles (Figure 58) and/or crucible slag (Figure 59). By far the majority of remains were completely corroded, however uncorroded prills were found preserved in the slag and areas of preserved metal were identified surrounded by corroded metal (Figure 60). Approximately a hundred individual lumps of corroded iron or iron-alloy with an average size of *c.*1 cm^3 were recovered from the crucible pit during the excavation. Around a dozen of these lumps were sectioned but were completely corroded even beyond the point of identifying any relic structures.

Another iron containing product found in the workshop was hammer-scale. The hammer-scale was the "fish-scale" variety and was collected with a magnet. The area of the highest concentration was around furnace 3. Other types of hammer-scale, such as that with a low iron content and high slag content commonly found as small spheres, were searched for by visually examining the sandy matrix associated with the magnetic hammer scale, however, none were found. This indicates that the metal that was being forged had a negligible amount of slag.

Corroded metal was also found on the interior side of some of the lids and walls. Unfortunately most of these droplets are completely corroded, thus their appearance and our working term, "rusty splashes". The densest concentration of this corroded metal is directly above the slag fin and the concentration of splashes generally decreases toward the top of the crucible wall. The rusty areas on some of the slag fragments are corroded prills. Loose corroded prills of iron and steel were also found with the use of a magnet in the crucible pit.

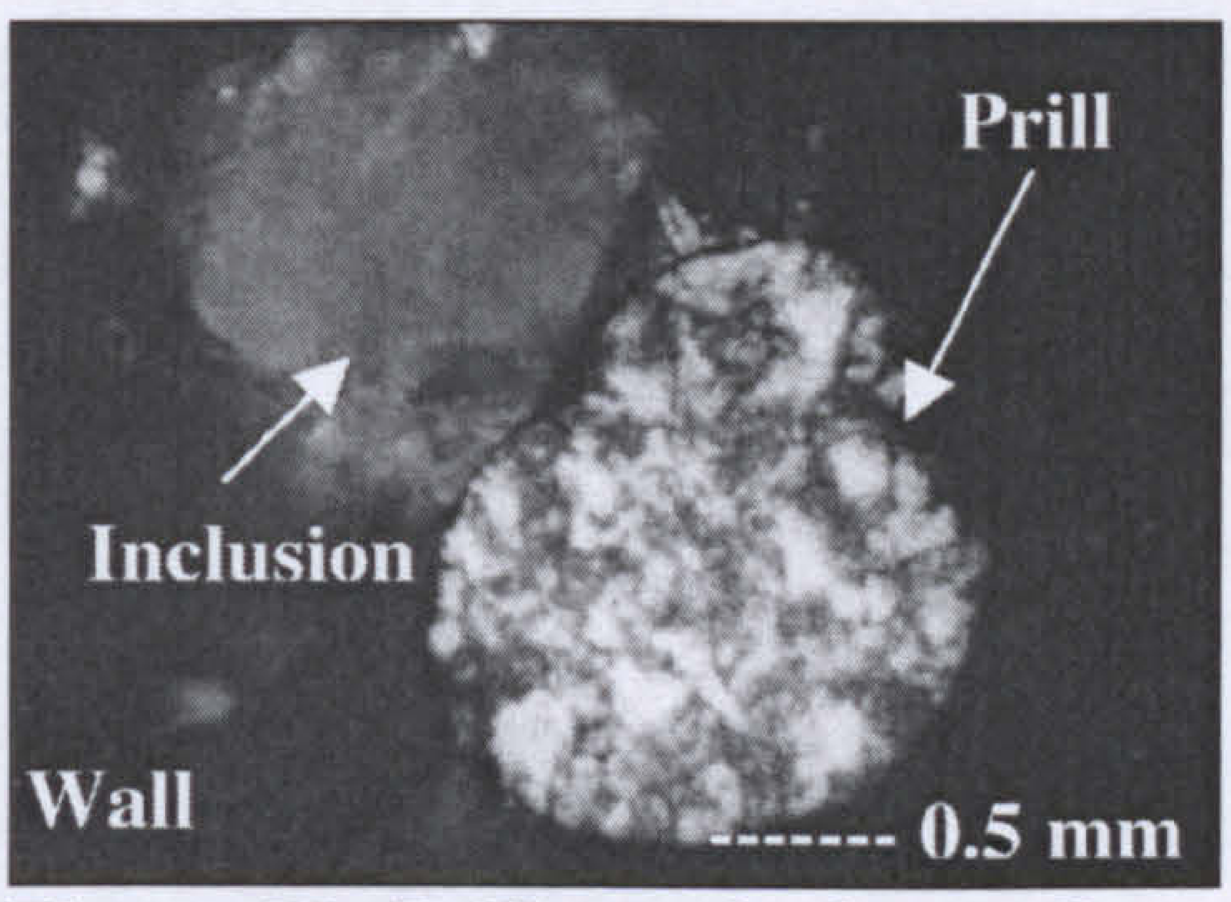


Figure 58: Prill attached to wall

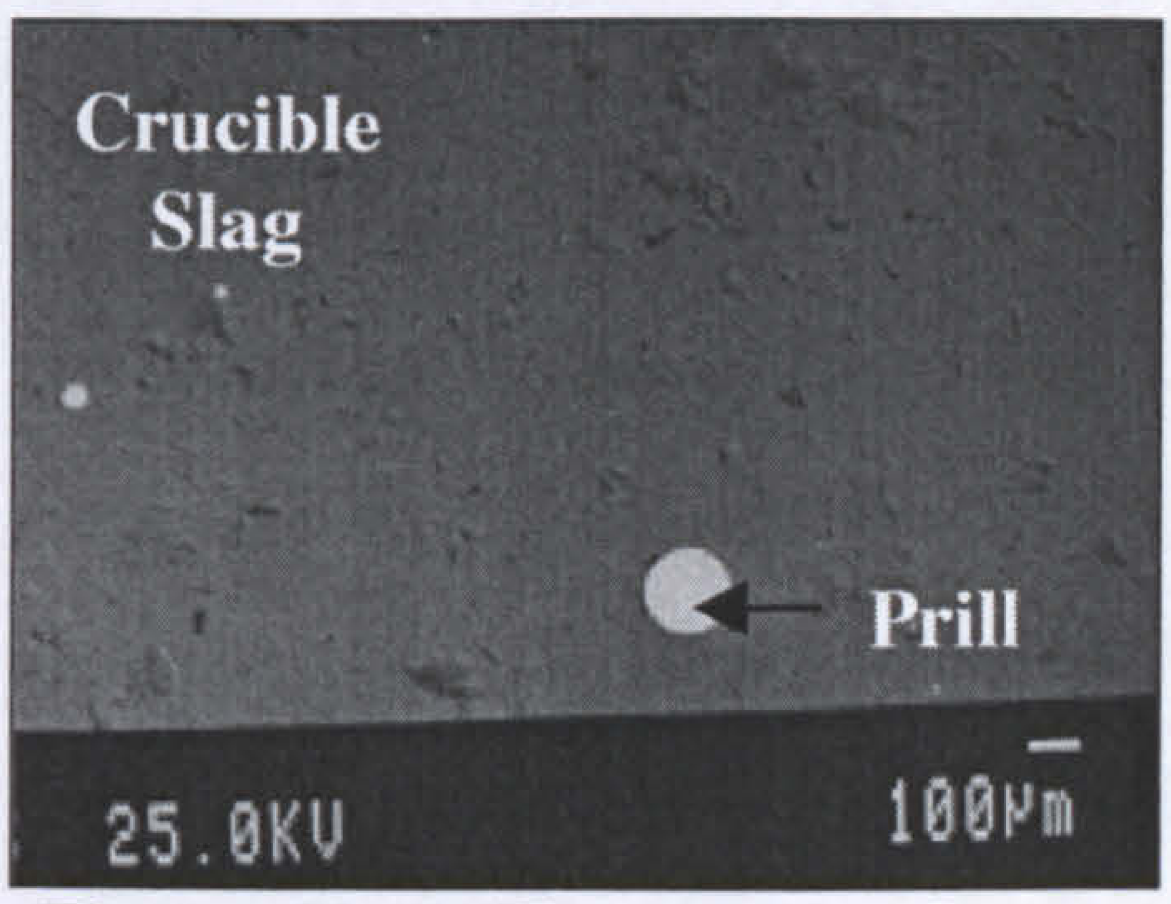


Figure 59: Prill A.6.12 in slag

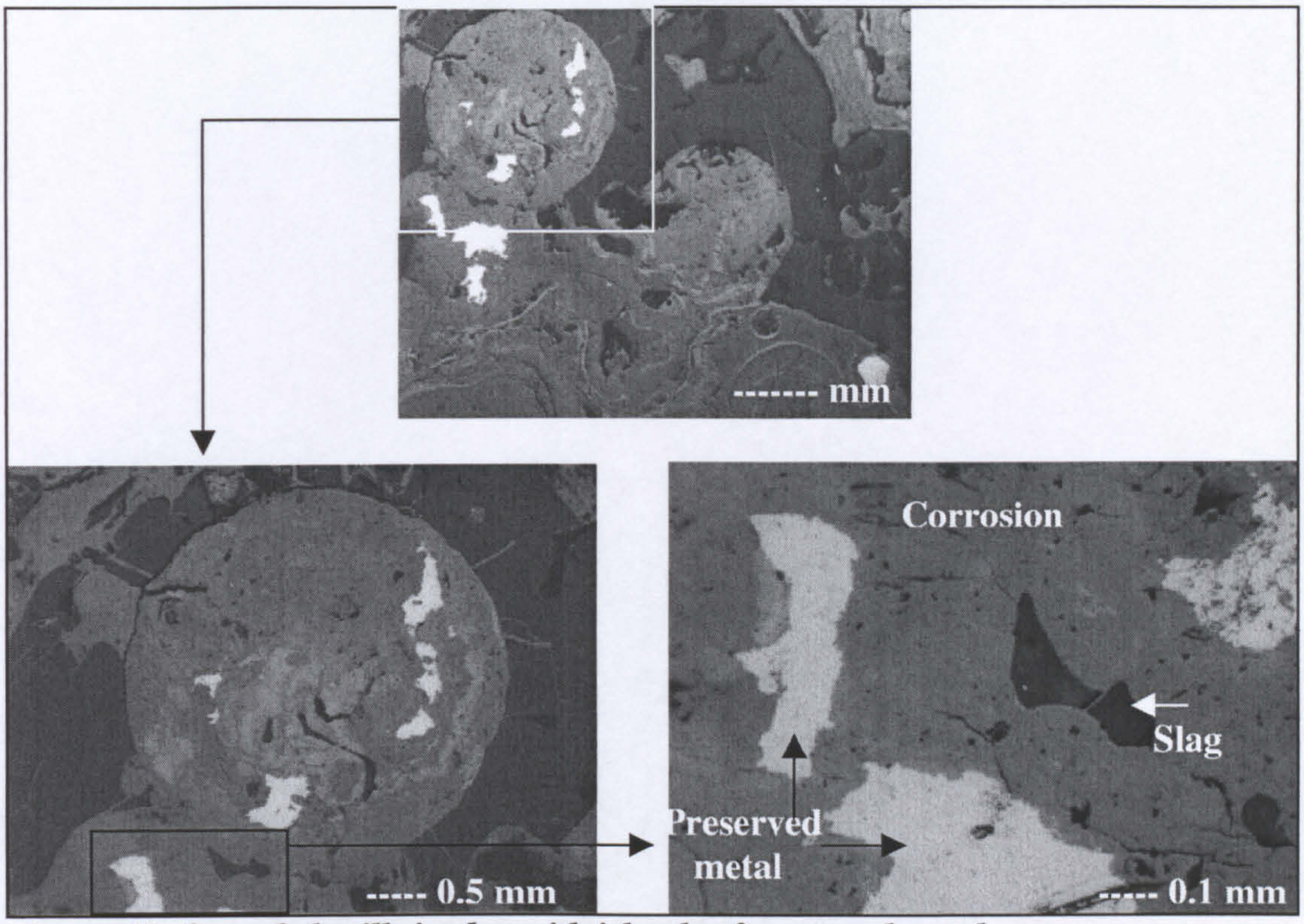


Figure 60: Corroded prills in slag with islands of preserved metal.

The identification of many of these prills as steel and the identification of the steel ingot (see below) indicated that the crucibles were from the production of crucible steel. The majority of prills are less than 10 µm in diameter. The microstructure of the prills was determined by using standard microscopy, although this was difficult due to their small size, and by observing backscattered images. All the pieces examined were either cast iron or steel. Flakes of graphite were observed in some small prills (Figure 61) indicating grey cast iron. White cast iron was also observed containing ledeburite (Figure 62). Ledeburite is associated with hypo-eutectic white cast irons and the microstructure is composed of austenite and cementite, or austenite's low temperature structure e.g. pearlite with cementite (Hume-Rothery, 1966, 318; Samuel, 1980, 21). Many of the prills are of hypereutectoid steel with a slow cooled pearlitic structure and idiomorphs were observed also indicating slow cooling (Figure 63).

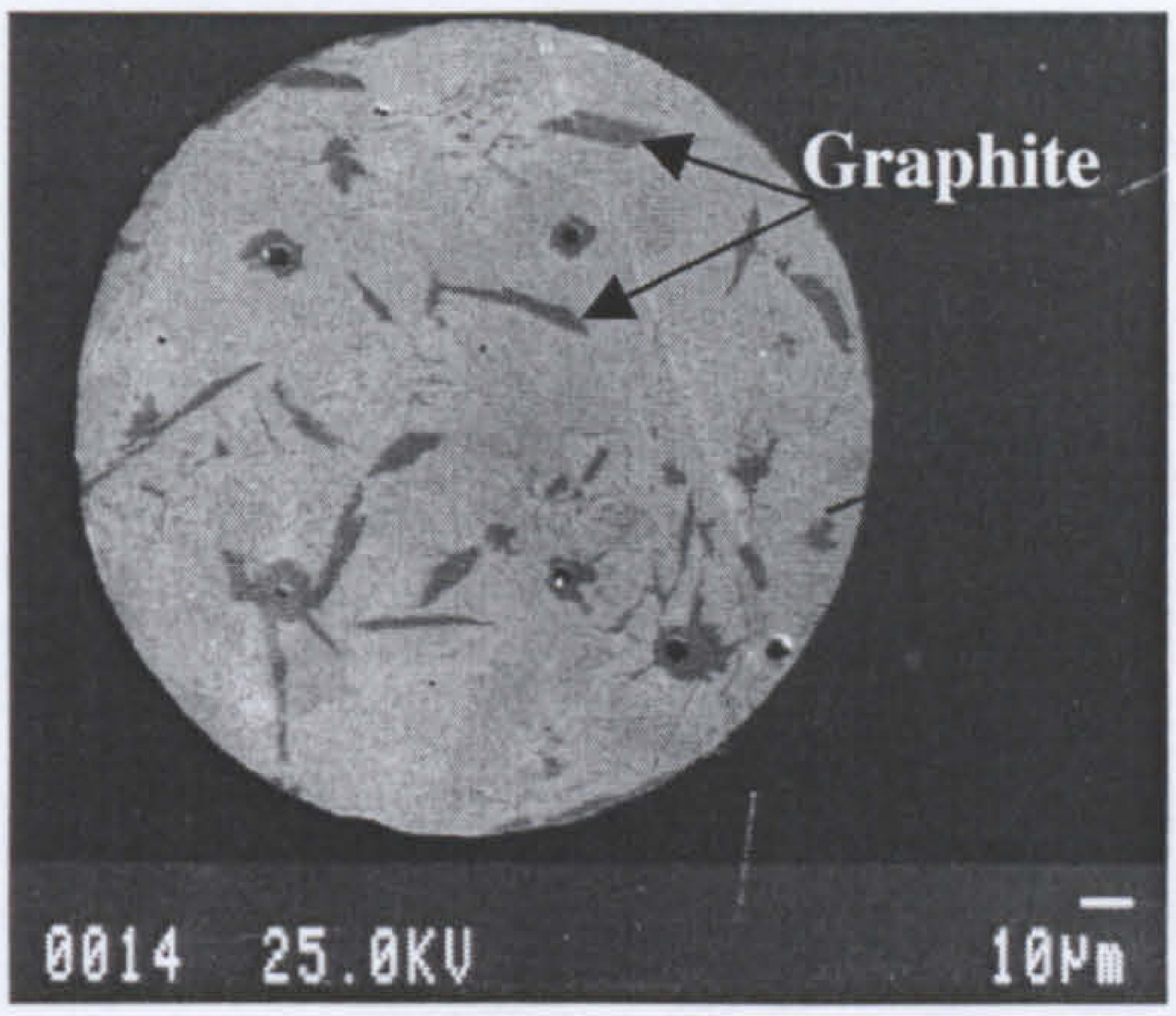


Figure 61: Prill A.4. 2 B is a grey cast iron prill with graphite flakes .

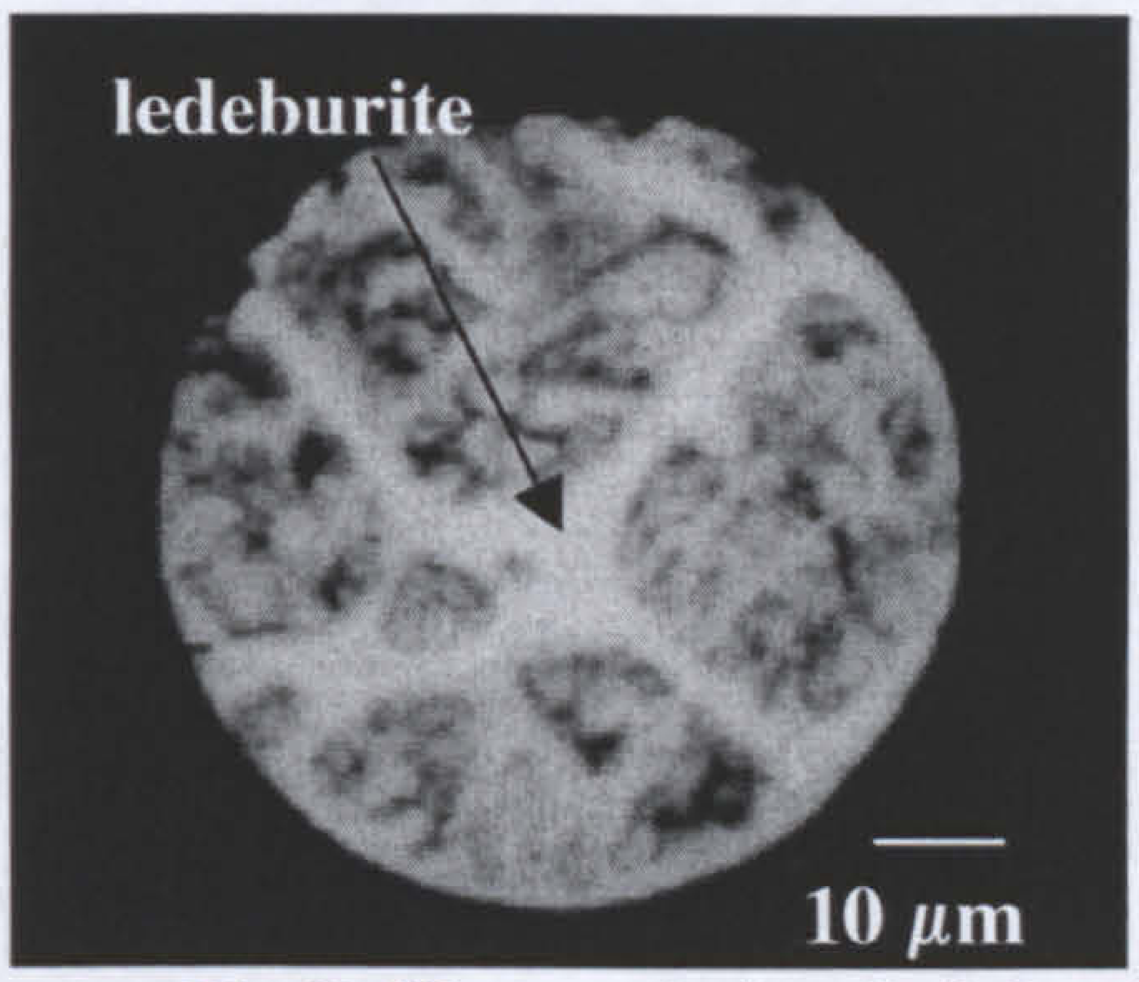


Figure 62: Prill containing ledeburite.

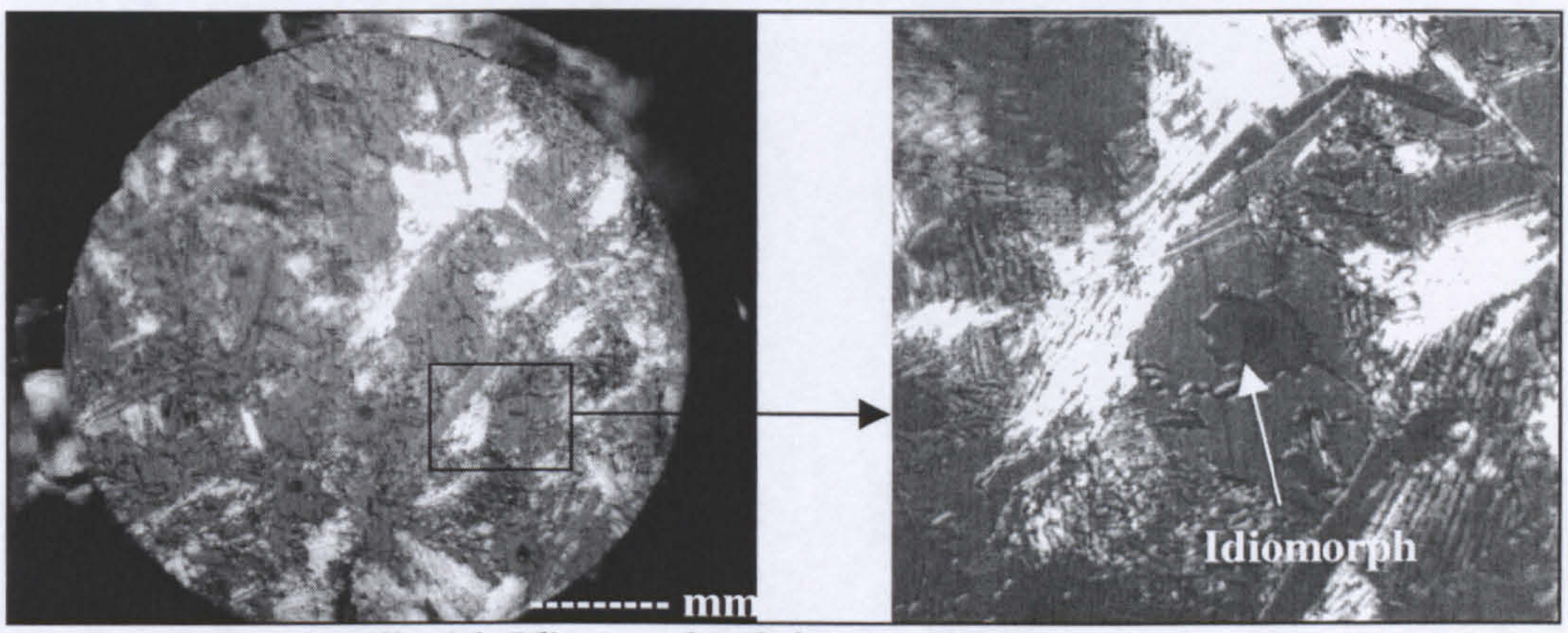


Figure 63: Steel prill with Idiomorphs (left), detail (right).

The crucible steel ingot is virtually entirely corroded with two small island of preserved metal. Etching in Nital revealed that the preserved metal is hypereutectoid steel, around 1.2-1.4% carbon consisting of grain boundary cementite and cementite needles with a coarse pearlite matrix. (Figure 64).

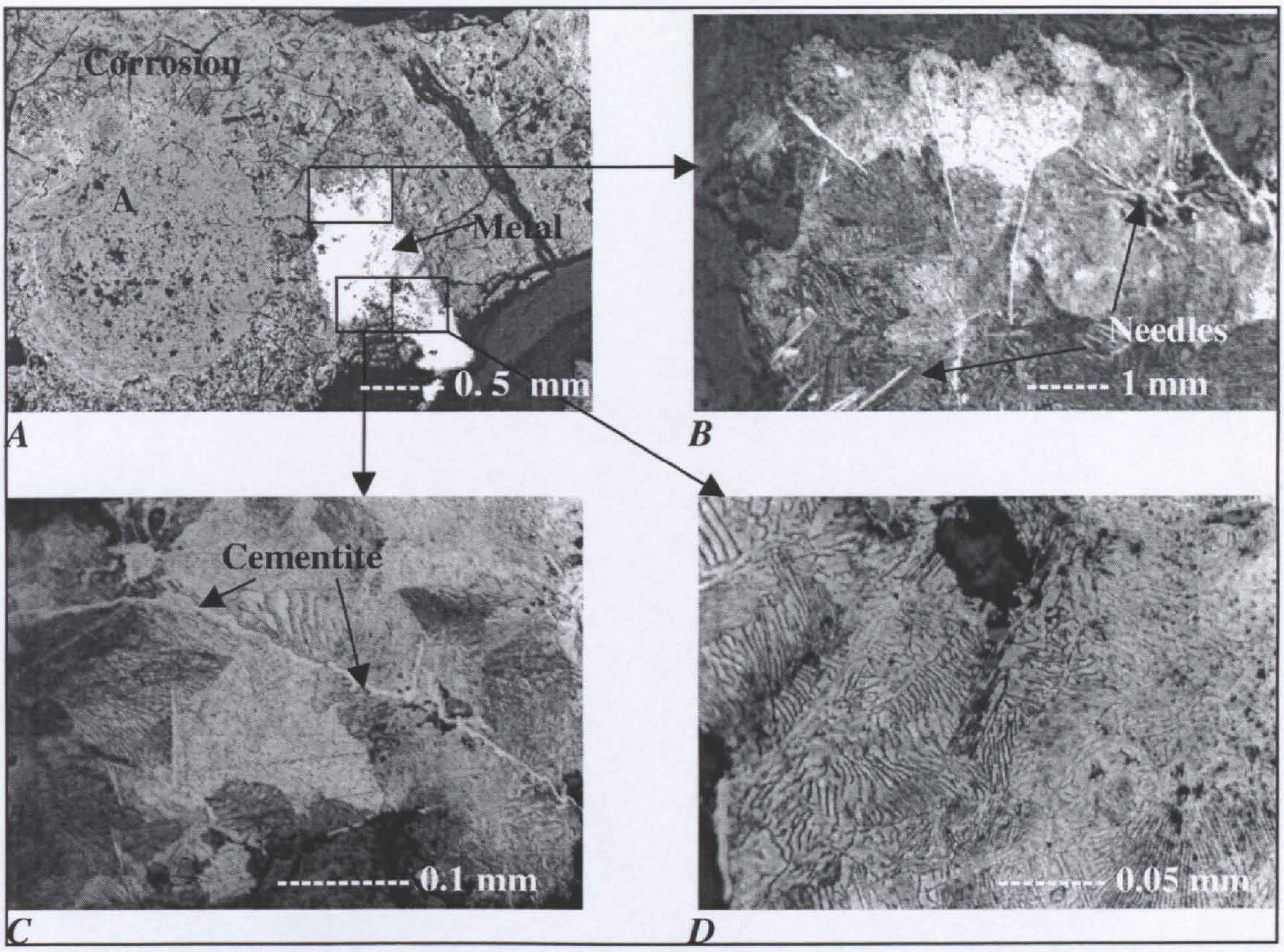


Figure 64: The crucible steel ingot after etching in nital. In photomicrograph A the corroded matrix surrounds the island of preserved metal. Cementite needles, and cementite at the prior austenite grain boundary appear in B and C. D illustrates the pearlite matrix.

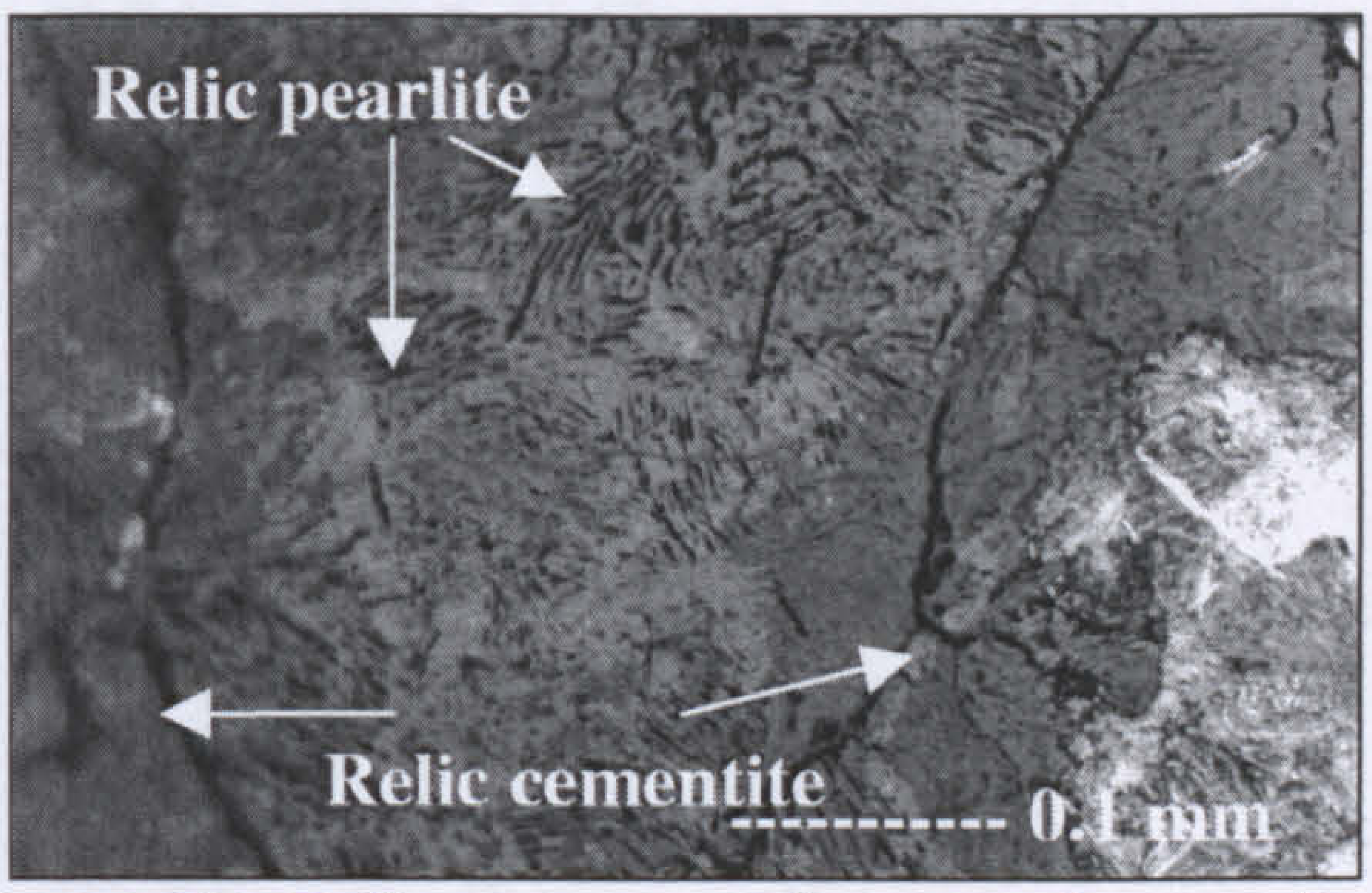


Figure 65: Relic structures in corrosion products

Relic structures of cementite needles and pearlite can be observed in the corrosion products (Figure 64A and Figure 65). In figure 64A, the circular area (A) has a different corrosion pattern than the surrounding area. The remnant pearlitic areas and grain boundary cementite appears to stop where the circular area begins. The area may just be a random corrosion feature, however, the circular nature of the area and the seemingly abrupt change in corrosion pattern suggest that this area originally had a different composition than the matrix. This area may have been part of the original metallic component of the crucible charge, perhaps a small wrought iron nail or similar objects with a diameter of about 15 mm, or a spherical pore filled with corrosion products.

Fourteen prills, from twelve samples, were analysed using EPMA at 25 KV. Two samples contained more than one prill and two prills from the same sample were analysed to compare their compositions. Spot analyses were performed on eight samples and line scans were performed on four samples. Line scans involved choosing a starting and ending point for the line and analysing points at 2 μm intervals. Line scans were performed to suggest the average composition of the prill and to determine if any wide variations occurred in particular spots. If wide variations in composition were found, this could have affected the assumed representative nature of the spot analyses. Although variations occurred, the average of three spots was considered to be reasonably close to the average composition of the prill. An area analysis of the entire prill was not performed because many of the prills were either too small, porous, or contained slag.

Details of the elemental composition of the prills and ingot can be found in Appendix G and a summary of the average compositions is presented in Table 12. Other elements analysed for but were either not found or the signal was not high enough above the background noise to be confidently relied upon as present include Si, Ca, Al, Ni, As, Ag, Ti, Au, V, Ba, and Cr. EPMA spot analyses and line scans were also performed on the crucible steel ingot. Line scans were performed on the ingot in the hope of determining a reasonably accurate average composition. The line scan was performed without a set relation to the directions in which the presumed dendrites were orientated.

Table 12: Summary of Elemental Composition of Prills and Ingot

	ID number	Fe	Cu	Mn	P	Total
Spot average	*7*	94	0.3	0.1	0.1	***94.4***
	8	97	0.3	0	0.03	***97.3***
	10	96	0.2	0.1	0.03	***96.3***
	11	95	0.3	0.1	0.0	***95.4***
	12	95	0.2	0.1	0.02	***95.1***
	13	94	0.3	0.3	0.1	***94.5***
	16	94	0.3	0.1	0.06	***94.4***
	34	94	0.1	0	0.1	***94.4***
Line Scans Average						
	19	94	0.1	0.2	0	**94.4**
	A.3.7	91	0.1	0.04	0.4	**92.0**
	A.3.7 prill 2	92	0.1	0.05	0.03	**92.5**
	5	96	0.3	0.06	0.1	**96.5**
	28 Double prill	94	0.2	0.05	0	**94.3**
	28 Small prill	94	0.2	0.05	0	**94.1**
	Merv ingot	95	0.2	0.06	0.03	***95.2***

The balance to 100%total is mostly due to carbon which was not analysed for.

All the prills and the crucible steel ingot analysed had between 0.2% - 0.3% copper. Whether this is from the ore, or whether copper was deliberately added is arguable. Initially it would be assumed that the copper was part of the original ore and indeed the heat-treated ore (discussed above) appears to have contained a small amount of copper. The percentage of copper is so small that it most likely came from the ore source. Indeed skarns often have copper associated with them. However, copper-alloy fragments were also found in association with the crucible steel workshop, a very small amount of copper could have been added to the charge. The presence of copper can strengthen steel and improve corrosion resistance (Rostoker and Bronson, 1990, 21). Smith (1960, 52) claims that Japanese smiths added copper to steel to enhance the grain pattern on polished blades. It is reasonable to assume that the copper may have had a similar effect on the crucible steel blades, but this has not been investigated.

There is an apparent relationship between the amount of manganese in the slag and in the prill in that slag. The more manganese there is in the slag, the more manganese in the prill. However, while the manganese content in the slag differs greatly, from around 2% to around 12%, that in the prills differs from not being detected to as high as 0.3%. The presence of manganese even in this low percentage is significant because it would promote the development of a Damascus pattern, if the ingot were forged in such a manner as to produce the pattern (see Chapter 3).

Phosphorus is present in all the analysed prills in quantities less than around 0.1%, and in the ingot the average quantity is 0.03%. Oberhoffer's etch was used to observe segregation in the crucible steel ingot because it has been determined to be a good indicator of phosphorus segregation in cast steel (Buhr and Weinberg, 1967). Areas that do not contain phosphorus are observed as darker grey areas and represent the primary dendritic stalks (Figure 66). The background area containing phosphorus appears light. The metal island is too small to observe any clear dendritic structure. The presence of phosphorus, even in these small amounts is particularly significant in crucible steels because during the solidification process, the iron, carbon, phosphorus eutectoid structure called steadite forms.

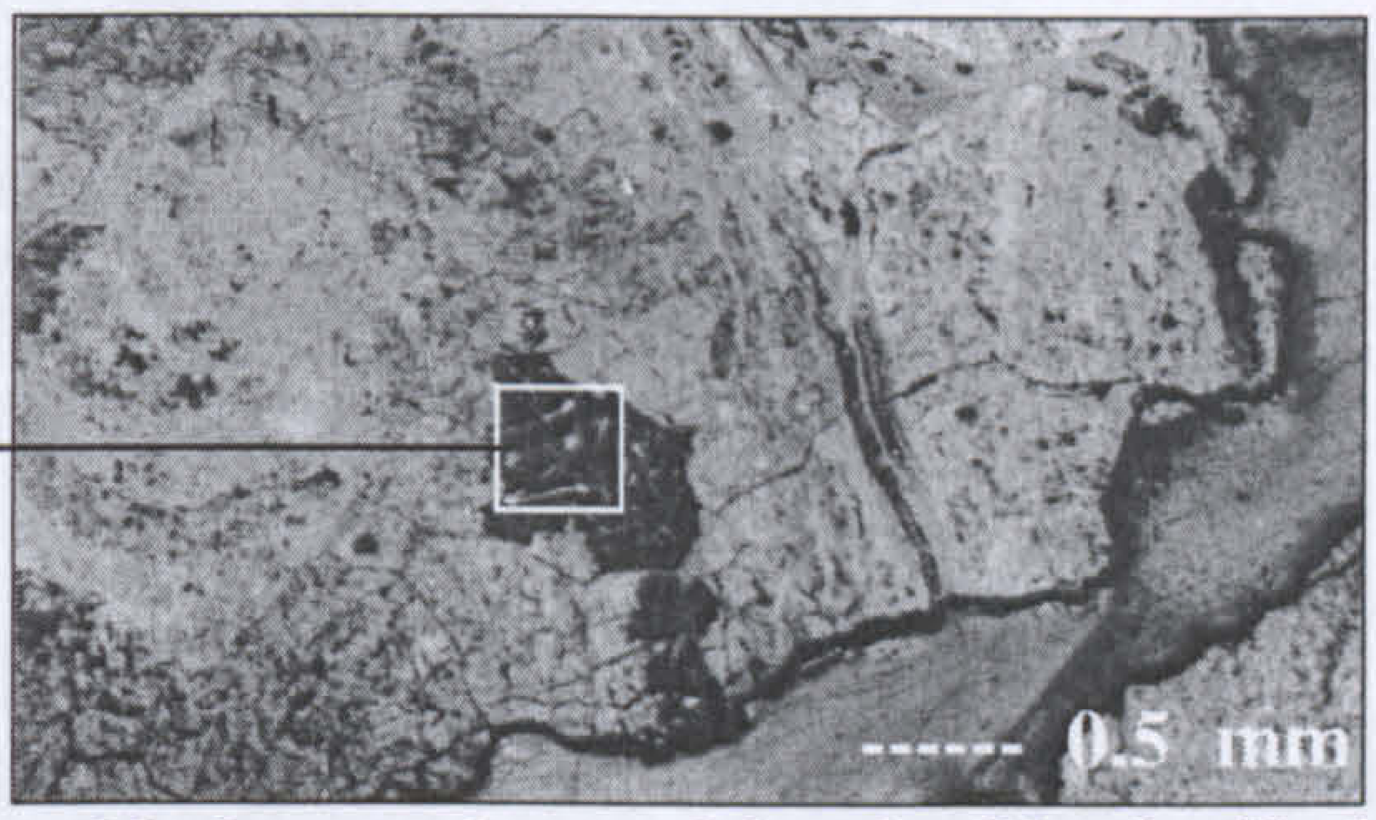


Figure 66: Ingot after etching in Oberhoffer's etch.

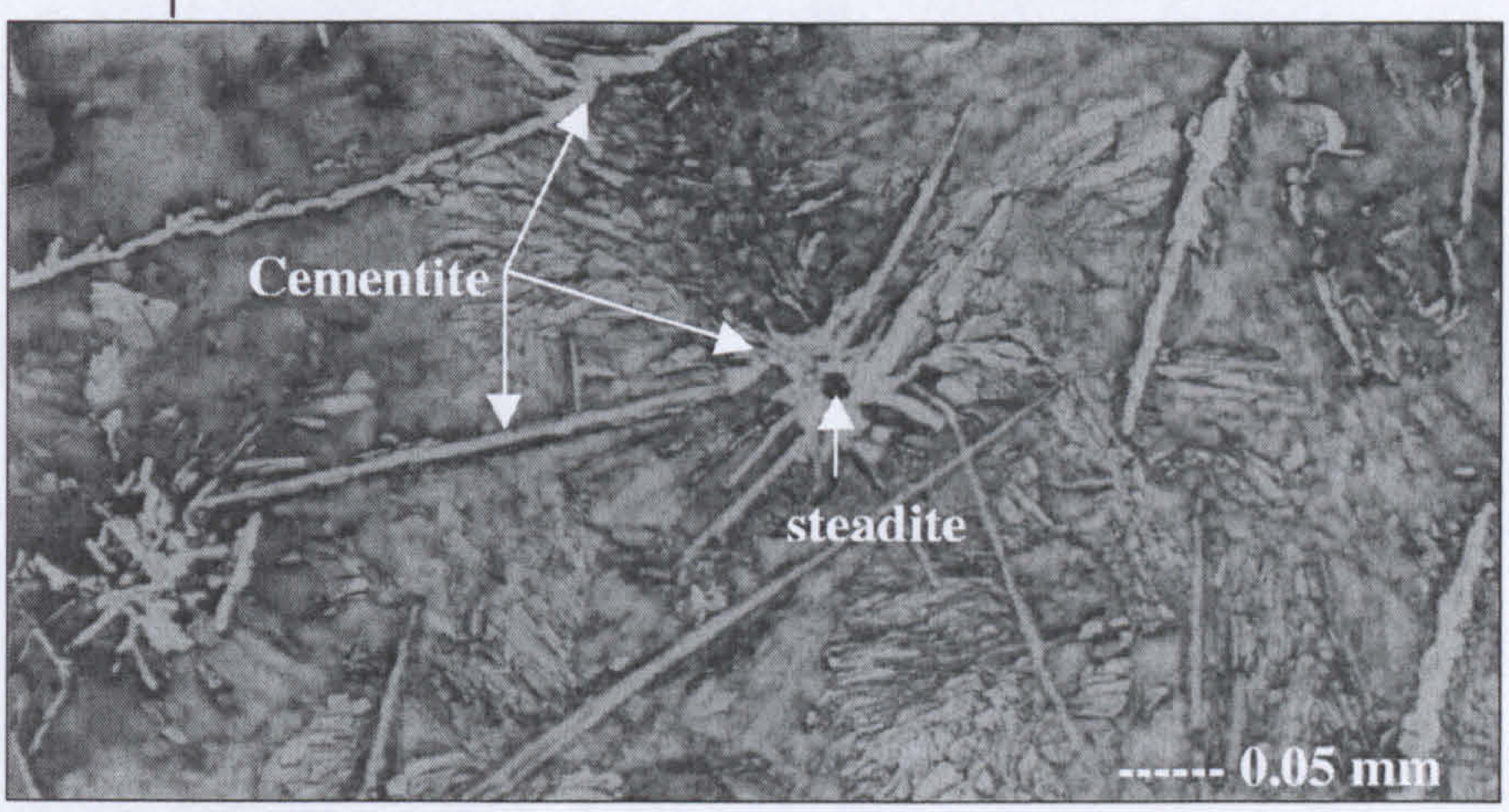


Figure 67: The crucible steel ingot etched in Oberhoffer's reagent. The light-etched areas are the phosphorus rich interdendritic areas. Cementite appears as starburst, needles and along the prior austenite grain boundaries. The spherical microstructure inside the cementite is steadite.

The examination of the iron and steel remains from Merv indicated that the carbon content of the metal in the crucible was between that of high carbon steel and cast iron. This internal area of the base is interpreted as the location of the melting and solidifying crucible steel ingot. Thc liquid steel would have conformed to this area when liquid. When the liquid steel cooled and solidified it would have retained the shape. Therefore, the size of the final crucible steel ingot can be deduced when the height of the slag fin can be observed in relationship to the base. The crucible steel ingot contained areas of hypereutectoid steel consisting of austenite grains surrounded by proeutectoid cementite. This suggests a firing temperature over 1300 ^{O}C because at this temperature steel with a carbon content around 1.2-1.4% C is composed of austenite and liquid metal. The metal would have had to be around 1450 ^{O}C for the steel to have been completely liquid. This, therefore, suggests that the crucibles and charge were fired to at least around 1450 ^{O}C, for a long enough period for the contents to melt.

Laboratory analysis documented prills consisting of high carbon steel in the crucible slag. This would be consistent with "cast" or pig iron being present as part of the original crucible charge but would not entirely preclude the possibility of the prills originating from a transitory high carbon iron region formed during a carburization process. It is possible given the small size of the prills, that they carburized or decarburized after being splashed up from the liquid metal. Cast iron prills could have been decarburized to steel when they splashed upward, indicating an oxidizing atmosphere inside the crucible. Or, conversely, steel prills could have been carburized, indicating a reducing atmosphere. The evidence of splashing is consistent with the occurrence of a carbon "boil" which occurs when iron oxide is introduced to pig/cast iron (Gilchrist, 1989, 347). However, the prills may be residual from the charge material which carburized *in situ* on the crucible wall (Rehren, pers.com.).

Since crucibles, often with attached prills, are found in abundance compared to ingots, it is important to assess how representative the prills' composition is to the associated ingot. From the archaeological evidence it is not possible to directly compare the composition of the ingot and prills since their relationship is not known. One could have been produced decades before the other. However, the elemental analyses of the prills and ingot from Merv all have a fairly similar elemental composition (94% Fe, 0.2 % Cu, 0.09% Mn, 0.06% P in prills; to 95% Fe, 0.2% Cu, 0.06% Mn, 0.03% P in ingot). The difference in metallurgical structures, from cast iron to steel, is the result of slight differences in carbon content (~ 1%). The carbon content of the ingot is important because it indicates if cast iron or steel was being produced in the crucible. Although, it was probably very difficult for the craftsmen to produce ingots with the same carbon content because only a slight variation in the amount of carbonaceous material would produce either cast iron or steel. The variation of structures in the prills, grey cast iron, white cast iron, and steel, may be characteristic of different ingots. The examination of an ingot and prills, formed during the production of the crucible steel ingot produced by Peterson (pers. com.) showed that they were both composed of grey cast iron. This suggests that prills are, for the most part, representative of the ingot, however, more studies on replicated materials could suggest how representative the prills are. Furthermore, considering that the ingots decarburized during annealing and forging (see Chapter 3), the carbon composition of the original ingot is not analogous to the carbon content of the final product.

The microstructure and segregation of elements in the Merv ingot are comparable to a replicated crucible steel ingot examined by Verhoeven and Jones (1987) (Figure 68).

Figure 68: As-cast crucible ingot etched in Stead's etch. The arrow indicates the dendritic cementite. The light-etched areas are the phosphorus rich interdendritic areas. (From Verhoeven and Jones, 1987, 168)

The identification of steadite in the Merv ingot is particularly important because crucible steel experiments, such as those performed by Verhoeven and Jones (1987), indicated that steadite required that the crucible steel ingots were forged at a temperature below the austenite transition temperature (see Chapter 3), which corresponds to red heat (around $700^{O}C$).

Glass

A selection was analysed to compare the glass' composition to that of the slag in order to assess whether or not the glass was possibly part of the crucible charge. Furthermore, the crucibles from Merv and those from Uzbekistan were initially identified as glass-making vessels (Abdurazakov and Bezborodov, 1966), therefore; the glass was also studied to investigate this remote possibility. Around two-dozen glass fragments were uncovered during the excavation of MGK 4. The fragments are less than around 4 cm in length, 2 cm in depth and 2 mm in thickness. Some of the fragments are more deteriorated than others but the colour can clearly be seen in the centre of the section. The colours and type of glass range from green to blue and clear vessel glass. Some glass samples have a relatively homogenous composition while others exhibit inhomogeneity when viewed using backscattered electron imaging. Reflected light microscopy of polished sections and secondary electron images revealed varying amounts of bubbles in the glass, usually in a preferred orientation. Seven pieces of different coloured excavated glass were analysed using EPMA spot analyses at 15 KV. (Table 13 and Appendix H).

Table 13: Summary of MGK 4 Glass Analyses

	SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	Fe_2O_3	MnO	X	Total
average	61%	5.8%	4.3%	8.4%	13.8%	3.9%	0.7%	0.3%	2.5%	97.5%
st. dev	+/-3.4%	+/-2%	+/-0.4%	+/-0.9%	+/-1%	+/-0.7%	+/-0.3%	+/-0.6%		

X = P_2O_5 + PbO + BaO + SO_3 + Cl + TiO_2 + CoO + CuO which appear at too low levels to state if they are there with certainty. Refer to Appendix H for details of the results. Elements analysed for but not detected were Sn, Sb, Zn, and Cr.

The main difference between the composition of the glass and the typical crucible slag is in the much higher soda content of the glass (*c.* 14%) compared to the percentage in the slag (*c.* 0.2%) even considering loss of sodium as a volatile during the firing process. This, and the very different ratio of silica to alumina (10:1 in the glass, and about 3:1 in the slag), is a significant difference even when one considers that the crucible fabric and material from the crucible charge, perhaps ash, may have contributed elements to the slag. Glass does not seem to have been a significant component in the crucible charge.

Reconstruction of the Process

The investigation of the remains of crucible steel production at Merv determined certain aspects of the crucible steel process as it was performed there. The discovery of a crucible steel ingot and the numerous fragments of crucibles found in the so-called crucible pit adjacent to furnaces indicate that crucible steel was produced in this workshop (Figure 69). Furthermore, the skill of the craftsmen and their concerns could be considered by assessing to what extent the materials, such as the clay, and techniques influenced how pragmatically the process was undertaken by applying the tenet that a technological procedure is "a system of choices made by the artisan" and "these choices depend on factors such as the raw materials, equipment and knowledge available to the artisan" (Keller, 1994, 60). This approach has been used by Shepard (1974, 361) to judge the skill of a given potter.

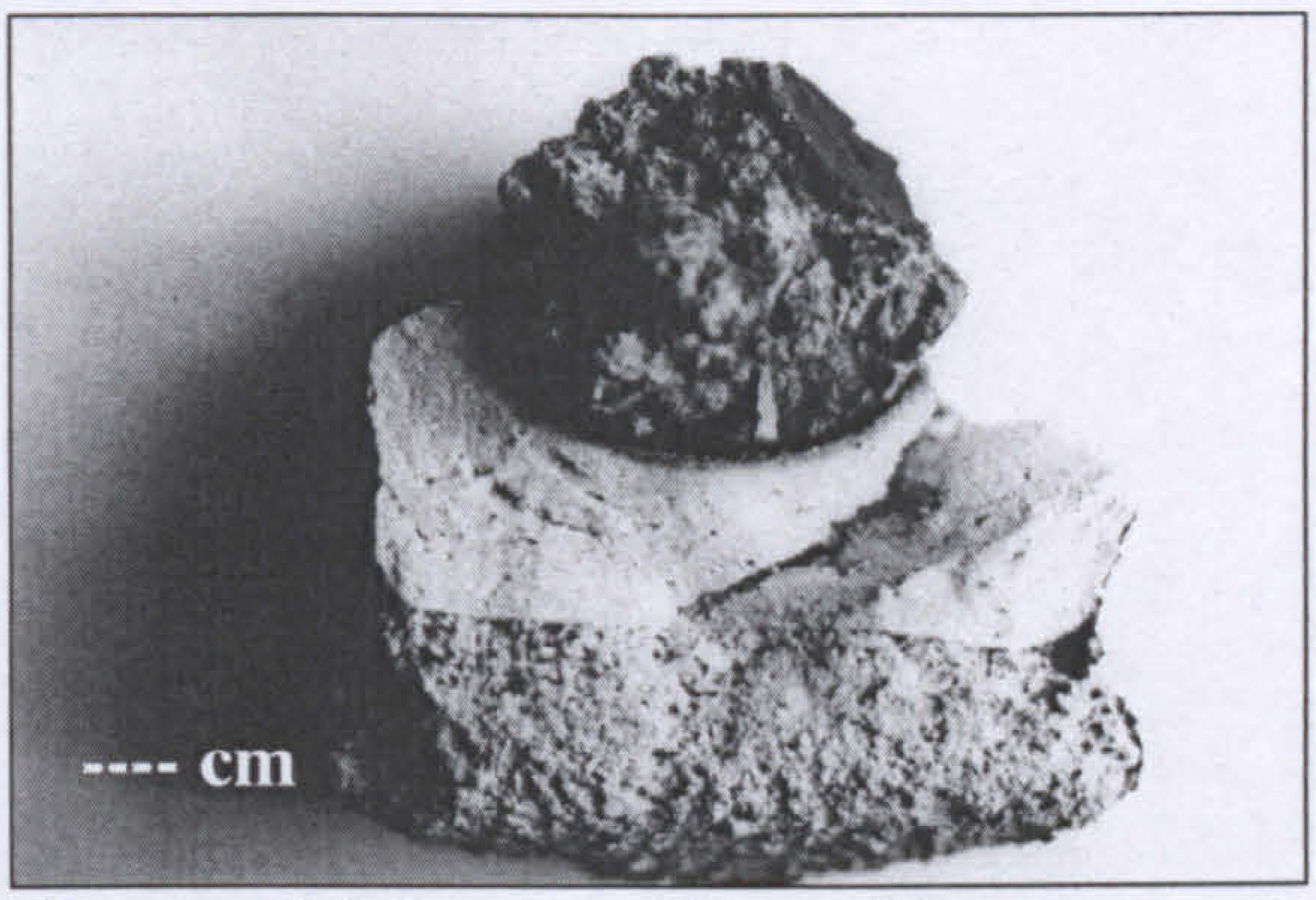


Figure 69: Merv crucible and Ingot

It is presumed that the craftsmen were indeed men because this is the traditional sex of the potters and ironworkers in Islamic society. The 14^{th} century treatise attributed to Abu'L-Qasim's discusses ceramic technology and it is his grandfather's signature, which appears on tiles (Allan, 1973, 165) suggesting that men were primary the potters. In addition, in Islamic texts addressing metallurgy, such as those discussed by Allan (1979), the authors discuss craftsmen, not crafts-women, indicated by the original authors particular choice of words. Ethnographic evidence from Central Asia also indicates that men are the potters and blacksmiths (Wulff, 1966). Therefore, there is no indication that women were either producing the crucibles or working with the iron. However, they may have performed subsidiary tasks in the workshop but there is no evidence for this either. Therefore, throughout this text the term craftsman/craftsmen will be used.

Thc crucibles were probably made in the same workshop that made the crucible steel. It was determined above that the crucibles were wheel thrown. The use of crucible grog in new crucibles, in the pads, in the furnace lining and on the furnace floor suggests used crucibles were available in the workshop where new crucibles were also made suggesting that the furnaces were not at a great distance from the pottery wheel. Theoretically, it is possible that the broken crucibles or grog were collected, moved to a different location where new crucibles were made and then returned to the crucible steel site. The charge, discussed below, had to be placed into the crucible before the lid was luted on, and the luting clay is the same as the crucible body. Therefore, at least some clay needed to be available in the steel-making workshop. In addition, moving the unfired crucible would cause added stress to the crucible fabric, thus increasing the possibility of failure during firing. Consequently, it appears most likely that the crucibles were made at the steel-making workshop.

It is not known whether or not a professional potter made the crucibles. However, a professional potter would not have been necessary because with only a brief period of training the craftsman could produce the crucible himself. In addition, the Islamic historian Al-Beruni wrote that the ironsmith Damasqi installed the furnace, devised crucibles, chose their size, and "selected the clays form which the crucible were to be baked" (Said, 1989, 219). It is reasonable to assume that the consistent diameter of the crucibles (*c.* 8 cm) was made by a craftsman using his hands as a measuring device.

Three factors that would influence the crucibles' performance and could be controlled by the craftsmen include the choice of clay, the shape of the crucible, and the choice and amount of inclusions. The crucible would have had to function at high temperatures, for a prolonged period of time without failure, such as cracking or slumping. It would have needed to do this while withstanding the weight of the crucible charge, the liquid steel against its walls, the weight of the plastic clay of its own walls, the weight of the fuel around its walls, in addition to resisting the attack by the slag on the inside of the crucible and the ash fluxing the exterior side of the crucibles' walls.

How much clay did the craftsmen at Merv need over the operating life of the workshop? The number of crucibles in the pit was estimated by calculating the average weight of crucible fragments in a given litre volume recovered from the pit, 82 g, multiplied by the number of litres in the pit, 12,282 (Appendix I). The result was that the pit contained 1,007,124 g, or approximately 1,007,000 g of crucible fragments. Assuming that they are all about the same weight and were constructed the same way, the estimated weight of a fired crucible was determined by weighing virtually complete fragments (such as lids and bases), in addition to weighing large fragments and multiplying the weight by its fractional inverse (i.e. a third of a wall fragment weighing 75 g was multiplied by 3 to estimate the weight of a complete wall as 225 g). The weight was estimated to be 842 g per crucible, or about 840 g. The number of crucibles in the pit was estimated by dividing the weight of crucible fragments in the pit by the average weigh of a single crucible (1,007.124 g. / 842 g = 1,196 crucibles). Since some crucible fragments were reused as grog in crucibles, for the furnace wall, or on the furnace floor, therefore to compensate for this, a rough conservative estimate of 5% was added to the calculation. The resulting estimate is that approximately 1250 crucible of the same type were used during the operating life of the workshop. Without considering the weight of water that would have been in the natural clay prior to firing (see Rice, 1987, 40), the minimum amount of clay needed to make all the crucibles would have been at least 1,000 kg. The clay for the crucibles was not the same as the local clay used for domestic ware, which is beige in colour and presumably would not have withstood the high temperatures, thus a substantial amount of clay needed to be transported to the workshop. Thus, the craftsmen were reliant on the importation of clay, for without the clay the process could not be undertaken.

There is evidence that the craftsmen at Merv used techniques that would conserve clay, including the use of grog and quartz temper, in addition to trimming the base of the crucible and adding a pad made of a separate, less refractory, material, thus suggesting that access to the clay was limited, and/or the price of this special clay was high. The extensive reuse of crucible fragments in the production of new crucible as well as in the pads and furnace floors indicates that the craftsmen were concerned about the supply of clay, and thus employed recycling measures.

The craftsmen formed the clay into a crucible; an easy form to create on a rotating device and the shape has good inherent strength. Evidence in Persia for the use of rotating devices to shape vessels dates from at least the first millennium BC (Wulff, 1966, 137). The thickness of the walls was an important consideration because thinner walls have lesser thermal gradients and therefore there is less thermal stress (Rice, 1987, 229), but thick walls were also needed to support the crucible charge during the process without failure. A balance had to be made between the walls being thick enough to withstand the pressure but thin enough to transfer heat, while not cracking during drying and firing. Thin walls require less clay, conduct heat better, and increase thermal shock resistance, and break easier for removal of the steel. The base needed to be heavier and thicker for balance, to withstand the load of the walls and steel while being partly composed of liquid phases during heating at very high temperatures, however heat conduction would be slower. The cylindrical shape, with gradually thinning walls and no sharp angles, yields benefits: it used a minimum amount of clay, reduced thermal strain and spread the internal stress of the contents evenly upon the walls thus reducing the chance of failure.

After shaping, the crucibles would have been left to dry, probably to a leather hard state, turned over, and the base would be trimmed. If the crucible were any wetter, the thin walls would deform under the weight of the thicker/heavier base. If the crucible were too dry it would be difficult to trim and might crack during drying or when the pad was applied. The crucibles could have been trimmed when upright using a piece of string or similar implement, but the exceedingly thin bases suggest otherwise. These thin bases would have probably ripped if trimmed while wet and standing upright.

The pads were attached to the crucible whilst the pad was in a plastic state and the crucible was probably leather-hard. This is supported by the observation at the interface between the pad and a crucible with an extremely thin base. If the crucible was in a plastic state, the pressure needed to attach the pad to the base would have deformed the crucible, however a plastic pad would not affect the crucibles' structure. Without the pad, the shrinkage during drying and firing would have caused the crucible base to crack and therefore, fail. The pad performed a number of additional functions. It lifted the crucible off the floor into the hottest part of the furnace located a few centimetres above the floor. It also prevented the crucible from firing to the furnace floor by acting as a separating agent; furthermore it reduced the amount of refractory clay needed to make the crucibles' base. The pad sintered on to the crucible base and was also joined by the exterior black glaze. After drying, the crucibles would be charged and the lids would be luted on. The join between the wall and lid shows no evidence of being luted after the wall was fired, such as a glaze layer. The hole in the Merv crucible is too small for the effective addition of crucible charge. Thus, the addition of materials during firing can be ruled out.

One of the major questions this research endeavours to answer is what materials were placed into the crucible to produce the steel ingot. Apart from the prills and the one crucible steel ingot, all other pieces of iron alloys found in and around the workshop were completely corroded, even beyond the identification of relic structures, therefore it was not possible to ascertain if these lumps were wrought/bloomery iron, cast/pig iron, or steel. They are, however, believed to be part of the crucible charge. Lumps of heated iron ore with varying amounts of slag like material were found adjacent to the site and small fragments of the same material were found inside the crucible pit. However, no associated metal was found. Therefore, the only directly linked evidence of what went into the crucible are the products: crucible slag, prills, and the ingot. The heated ore and its associated slag-like material is the only iron rich material that was not inside the crucible that can be studied that might hint at the crucible charges nature.

The volume of the average steel ingot was calculated according to $V=\pi r^2 h$. The internal radius (r) of the base area is about 3 cm and the height of the ingot, based on height of the slag fin from the base of the interior of the crucible is 10 cm, thus resulting in a volume of 283 cm^3, or considering that the internal diameter increases towards the top of the crucible, approximately 300 cm^3. This equals about 2.4 kg of iron (300 cm^3 x 8 g/cm^3; the approximate density of iron). Some of the ingots were smaller with a height around 8 cm, which would result in an ingot weighing around 1.8 kg. Therefore, if 50% of the crucibles were small, the average weight of steel produced by each crucible was approximately 2 kg, allowing for the hemispherical base of the ingot. The estimated total number of crucibles was 1250, multiplied by the estimated average weight of the ingot, 2 kg, suggests that at least 2500 kg of steel were produced during the occupation of the workshop.

According to replication attempts, there are four possible methods of making crucible steel, each with numerous variations (see Bogachev, 1952, 53-65 and *Chapter 3*). Archaeological and textual accounts suggest two additional methods. It was against these six processes that the evidence from Merv was compared in order to determine the most likely one used.

1) Direct reduction from the ore;
2) Melting and casting steel into a mould;
3) Decarburization of cast iron by oxidizing liquid cast iron;
4) Decarburization of cast iron with iron oxide;
5) Reacting iron and carbon (carburisation) and;
6) Co-fusion of cast iron and bloomery/wrought iron.

Although heated high quality iron ore was found in and adjacent to the crucible steel site, the crucibles could not have been used to smelt iron ore to steel. The low volume of slag inside the crucibles, the homogenous nature of the slag within a single crucible and between the crucibles suggest that the crucible charge was iron-rich with few non-metallic elements. More importantly, the amount of ore and charcoal needed to reduce ore to steel, and in places produce cast iron, would have exceeded by far the size of the crucible. Assuming that the maximum height of the interior of the crucible was 20 cm and the maximum average radius was 3.5 cm, the maximum volume of the crucible would be 770 cm^3. Using the same method but with a radius of 3.25 cm because the slag is close to the centre of the crucible, the volume of the crucible slag is estimated to be a maximum of 17 cm^3 (thickness roughly 0.5 cm). However, because one side of the slag has vesicles, and there is a "fin" of slag around the circumference at the slag/wall interface which appears to become thinner as it progresses to the interior of the crucible, rather than being of equal thickness across the entire ingot, the volume of the slag is probably less than about 15 cm^3.

Rehren and Papakhristu's (2000) model for estimating the volume of raw materials necessary to produce an ingot of a particular size was applied here. Their model is simplified to only consider the amount of carbon needed to reduce a high quality iron ore to an iron ingot and does not account for factors including the final carbon content of the ingot, addition of fluxing agents, charcoal ash or erosion of the ceramic body. Their calculations are based on the simplified reduction process FeO + C = Fe + CO and assumes an ideal stoichiometric reaction (2000, 59).

Using the average estimate of the weight of an ingot as the starting point, the calculations of the total volume of iron ore and charcoal to produce an ingot of 2 kg are as follows:

- 2 kg metallic iron equals approximately 2.57 kg (2.5 kg used for ease of the calculation) of iron oxide containing 0.5% kg of oxygen.
- 0.5 kg of oxygen in iron oxide requires 0.4 kg of carbon to form carbon monoxide.
- Assuming the density of iron oxide is 5.6 g/cm^3 and of charcoal is 0.5% g/cm^3.
- The volume of 2.5 kg of iron oxide is about 450 cm^3, and of 0.4 kg of charcoal is 800 cm^3.
- The total volume of the necessary crucible charge would be 1250 cm^3.

The calculated volume of the crucible is only about 770 cm^3. This is less than 2/3 of the volume necessary to reduce pure iron oxide to an iron ingot. Therefore, the use of the crucibles to directly reduce the ore to steel can be excluded, thus eliminating this process. Consequently, the calculation indicates that the majority of iron in the crucible charge was metallic even before the steel making reaction took place.

The second possible method is the casting of liquid metal. The Islamic writer al-Jildaki mentioned a crucible steel process that appears to have comprised of casting liquid steel into moulds (Zaky, 1979, 206; Al-Hassan, 1978, 36), however, there is no evidence suggesting that this process was used here. The broken crucibles and the coarse pearlite microstructure of the ingot indicate that they were cooled inside the furnace; therefore steel was not cast in the workshop. In addition, no moulds or fragments of moulds were found in the workshop. Also, lidded crucibles, as those from Merv, are not suitable for casting.

The third and fourth possible processes both involve decarburizing cast or pig iron in a crucible and were both probably used in antiquity to produce steel. Al-Jildaki discusses what appears to be a decarburization method and decarburization of cast iron was used in China (see Needham, 1980, and *Chapters 3 and 4*) but evidence for this method is lacking at Merv. At the present time there is no evidence for the production or use of cast iron in Central Asia before modern times. In addition, known traditional decarburization methods utilize an open crucible or hearth to allow access of oxygen to the metal. At Merv the crucibles had a lid, thus eliminating this method. Adding oxygen to the cast iron in a different way, such as iron oxide, can also decarburise cast iron. However, the final carbon content would be difficult to control. The conclusion is that neither of these two methods were used at Merv.

Thus, having ruled out the possible reduction of iron ore or decarburization of cast iron, ore or cast iron as the potential primary charge material have been removed. By process of elimination, the only iron products, which could have been used as the primary charge materials, are bloomery wrought iron or steel. Each of these could have been placed into the crucible as part of the charge (see Chapter 3 for discussion).

Bloomery and consequently wrought iron were produced in Central Asia during the Islamic period. Since wrought iron is made from bloomery iron, the only distinguishing feature between these two is the amount of slag and the (iron's) level of consolidation. Consolidation and the removal of slag involve forging the bloom, thus requiring extensive labour and fuel. Blooms are often consolidated near the place of smelting, however, the pieces of heat-exposed ore found at Merv suggest that they were not consolidated before being transported to Merv. These heat-exposed ore fragments may have been part of the bloom which were removed and discarded because they did not reduce to metal. Their high iron content and gangue minerals are similar in elemental composition to the iron and slag, particularly the presence of calcium, magnesium, phosphorus, and copper, suggest they are related (see *Slag and Heated Ore* above).

There would have been no need to consolidate the bloom before being placed into the crucible, as the crucible steel process would have removed the slag and consolidated the metal when it turned liquid. Indeed, any voids would have assisted the diffusion of carbon by providing additional surface area (Rehren and Papakhristu, 2000). Forging the bloom would have used a considerable amount of fuel, a material which would have been in much demand at Merv due to the many workshops engaged in pyrotechnic crafts, but undoubtedly expensive because of Merv's location as an oasis city, virtually surrounded by desert. Thus, consolidating the bloom would have been unnecessary and wasteful.

Any slag from the bloom would have also been beneficial to the crucible steel process. Iron oxide in the slag could have reduced to metal (see *alternative arguments* below). In addition, experiments performed by Verhoeven (see *Chapter 3*) indicated that slag was a beneficial factor of the process because ingots produced without a slag covering cracked during forging (Verhoeven, pers. com.). Furthermore, Verhoeven *et al.* (1996, 17-18) suggest that slag controls the oxygen activity in the crucible melt and might introduce some additional elements, but concluded that slag has no direct role in the formation of the Damascus pattern. Considering the finds of extraneous bloom material around the workshop, the benefits of slag in the crucible, the possible relationship of the crucible slag to bloomery slag, and the cost of consolidating a bloom, it is concluded that bloomery iron, rather than wrought iron, was placed into the crucible.

Distinguishing between the final two processes, carburization of bloomery iron and the co-fusion of two different types of iron alloys, is more difficult because both methods are known to be traditional crucible steel processes with supporting literary and ethnographic or archaeological evidence (see *Chapter 2 and 3*). At the present time neither have known distinguishing features that would remain in the archaeological record and more research is needed to better compare the crucible steel remains from known sites, including determining the elemental compositions of the slags from different locations, in addition to replication experiments. However, the absence of evidence for cast iron in Central Asia at this time makes the latter method appear less likely than the former. Also, co-fusion would not require such a large crucible (see below).

Having determined that the bulk of iron in the crucible prior to firing was most likely bloomery iron, this leaves to identify the carbonaceous materials necessary to transform the iron to steel. The amount and type of carbonaceous material put into the crucible along with the bloomery iron can be suggested by assuming that the volume of the crucible was the smallest necessary to produce the desired steel ingot. The examination of the crucibles, and considerations of the geological environment around Merv, indicated that methods to reduce thc amount of clay needed per crucible were implemented at Merv (see above). Therefore, it may be assumed that the dimensions of the crucibles were chosen to minimize the amount of clay necessary, thus reducing waste of the apparently precious high quality clay.

It is argued that the volume of the crucible (*c.* 770 cm^3) was the smallest volume necessary to produce the desired product, a steel ingot *c.* 250 - 300 cm^3, from bloomery iron and a carbonaceous material. For simplicity, additional materials that may have been placed into the crucible, such as fluxing agents or additional elements such as manganese (see below), are not considered in these calculations. Evidence provided by the crucibles indicates that they were unfired when the charge was placed into them (see *Crucibles*). Therefore, the charge was not forced or packed into the crucible, as this would have produced stress on the crucible walls, which would initiate cracks, thus causing the process to fail.

The metallic component of the crucible charge is assumed to be the roughly 1 cm^3 iron fragments, found corroded during the excavation of the workshop (see *Iron and Steel* above). The expansion due to corrosion is not considered here because the calculations are approximate. The volume of the largest condensed products was *c.* 315 cm^3 (300 cm^3 iron + 15 cm^3 slag) after firing. This suggests that the iron charge contained around 6% slag, which is a reasonable amount of slag for a not particularly consolidated piece of bloomery iron, thus also supporting the belief that this was the iron charge. In the following calculations, the amount of crucible charge needed to produce a larger ingot is given in parentheses.

In order to suggest the volume of 2 kg (and 2.4 kg) of iron in 1 cm^3 pieces, a simple experiment was conducted. An egg-shaped potato (a similar shape to a 2 kg ingot) around 250 cm^3 was cut into 1 cm^3 pieces and placed into a pint glass, which had an internal diameter of around 6 cm at the base, flaring out to 7 cm in the centre and 8 cm at the top, thus a similar shape to the crucible. The height of the potato pieces reached 8.5 cm, thus the raw volume was 327 cm^3, an increase of about 31%. Assuming that the bloomery iron pieces were more irregularly shaped and contained voids, another 4% was added resulting in an estimate that the volume of the loose pieces is roughly 35% greater than the condensed ingot. Based on economic considerations of the size of the crucibles discussed above, the crucible charge presumably reached the top of the crucible prior to firing (*c.* 770 cm^3). The 327 cm^3 equalled three handfuls. Therefore, the amount of bloomery iron for a 265 cm^3 ingot (or 315 cm^3 for the larger ingot) with slag fin would have taken up around 360 cm^3 (425 cm^3) of space, leaving 410 cm^3 (345 cm^3) of space for additional materials.

The following scenarios are based on the assumption that 360 cm^3 (425 cm^3) of loosely packed pieces of bloomery iron were placed into the crucible with one of the following materials: charcoal, plant matter, or cast iron. Metallography of the crucible steel ingot uncovered at Merv indicated that the ingot contained approximately 1.2-1.4 % C. For simplicity, and although some crucible steel products from other places are known to have been composed of steel with lower carbon contents, less than 0.8% (see Chapter 4) but considering that the metal would have lost some carbon during forging, the crucible steel ingot is estimated to have initially contained 1.5% C. In order to raise 2 kg (2.4 kg) of iron to steel with a content of 1.5% carbon, 30 g (36 g) of carbon are necessary, excluding extra carbon that would convert to gas in the atmosphere inside the crucible and left though the hole in the lid.

Scenario 1: Charcoal

It was established above that it would take 30 g (36 g) of carbon to raise 2 kg (2.4) of iron to 1.5% carbon steel. This would take up approximately a volume of 60 cm^3 (72 cm^3) assuming the density of charcoal is 0.5. If the density of the charcoal were closer to 0.25 (Peter Crew, pers. com. with Th. Rehren) then the volume of charcoal necessary would be closer to 120 cm^3 (144 cm^3). Using the higher volume and assuming that 35% of the volume of the space between the charcoal are voids, the same as the iron, then the total volume of the charcoal needed in the crucible would be 162 cm^3 (194 cm^3). This would result in 248 cm^3 (151 cm^3) of extra space inside the crucible. Considering extra carbon for the atmosphere, there would still be about 6 cm (4 cm) left vacant at the top of the crucible (assuming the internal radius at the top of the crucible is 3.5 cm).

Scenario 2: Plant matter

During the conversion of plant matter, usually wood, to charcoal, the resulting volume of the charcoal can vary depending upon many factors including the species, age, size, dryness and process of converting the wood to charcoal (see Percy, 1861, 128-132). Based on Percy's record of the volume of charcoal to wood (1861, 129-130), the volume of charcoal was around 60% of the original wood, or 40% of the volume was lost during the conversion to charcoal. The plant matter placed into the crucible may not have been wood but could have been leaves, or fruit rinds, as these materials are mentioned in ethnographic and Islamic texts (see Chapter 3). The volume of the plant matter will also depend on whether it is fresh or air/sun dried, therefore it is reasonable to assume that the volume of plant matter would be approximately twice the volume of charcoal derived from it.

Above it was estimated that 120 cm^3 (144 cm^3) of charcoal was required in the crucible. Assuming that the volume of charcoal is 50% of the original plant matter, roughly 240 cm^3 (288 cm^3) of plant matter would be needed in the crucible to raise the carbon content of the iron to 1.5% carbon steel. Once again adding 35% of volume to account for voids between the pieces, the total volume of plant matter in the crucible would be about 324 cm^3 (388 cm^3). The resulting volume of plant matter needed is close the total estimated space for carbonaceous material in the crucible, 86 cm^3 (- 43 cm^3). The charge for the estimated average sized ingot would have left 2.2 cm of space remaining at the top of the crucible, whereas the larger crucible would require the crucible to be 1.1 cm taller. Thus, the entire internal volume of the crucible would have been used.

The most likely type of plant matter would have been leaves or wood. The volume of dried leaves or wood necessary to raise the carbon content of the iron to around 1.5% C, was roughly determined by two simple experiments. Conservatively estimating that at the least 10% of the weight of the dried leaves was composed of water and other compounds, the amount of dried leaves necessary to raise the carbon content of iron to that of steel, would have exceed the amount of space available. Wet leaves (oak) weighed 100 g wet and 40 g after drying at room temperature for approximately fifty days. The volume of the dried, but not crushed leaves was not calculated, but visually it appeared to be over four times the size of a crucible. 40 g of dry leaves crushed was over 950 cm^3, thus far greater than the remaining crucible volume. However, it should be kept in mind that oak leaves were used in this experiment because they were readily available, rather than leaves that are commonly found in the desert. This substitution was thought to have not significantly changed the final result that the necessary amount of crushed leaves exceeded the volume available, thus eliminating leaves as the major carbonaceous component of the crucible charge.

Chips of dry hardwood (commercially available BBQ mesquite chips) with the largest size 2 cm^2 x 0.5 cm were used because they were composed of randomly sized pieces of seasoned wood and could be used to represent virtually any wood. Although there can be a difference between the weight and volume of wood, depending upon factors such as what type of species the wood is from, its age, and what part of the plant was used, these differences would not strongly influence the results of this test. Above it was estimated that around 410 cm^3 (345 cm^3) of space remained in the crucible for additional matter. This is close to three and a half (three) handfuls of dry wood. Three handfuls weighed 100 g and had a volume of 350 cm^3. The volume of charcoal is around 60% of the original wood (Percy, 1861, 129-130), and the remaining weight would be below 1/3 of the original (Percy, 1861, 130), having only carbon remaining, but again this depends on the type of wood. Thus, roughly 100 g (108 g) of dried wood with a volume of 350 cm^3 (378 cm^3) would be required. Assuming that some carbon was lost to the atmosphere, around three or four handfuls of dried wood would probably have been used.

Scenario 3: Cast iron with 3% carbon.

If cast iron were added to wrought iron, the cast iron would also contribute iron and associated elements, to the final steel ingot, in addition to carbon. The carbon content of cast iron can vary from around 2% to 4%; therefore 3% was used in this calculation. To raise 2 kg (2.4) of iron to an average of 1.5% carbon the crucible charge would have to consist of 1 kg (1.2 kg) of bloomery iron and 1 kg (1.2) of cast iron. Assuming that the raw density of the cast iron was similar to the wrought iron, the total volume of the iron containing material placed into the crucible would have again been around 360 cm^3 (425 cm^3), leaving 410 cm^3 (345 cm^3) of the crucible empty or about 10 cm (9 cm) of the top of the crucible empty, thus wasting valuable clay.

Based on the amount of volume needed to carburize low carbon iron, each of the above scenarios could have been used at Merv. However, when one considers that the craftsmen endeavoured to use as little clay as possible in the construction of the crucibles, the volume of the crucible becomes a significant consideration. Given the size of the crucible, and assuming that the craftsmen created crucibles with the lowest possible volume required to contain the crucible charge, the most convincing possibility is scenario 2, the addition of plant matter, probably wood, to bloomery iron.

Table 14: Summary of Evidence of Crucible Charge

Process	Evidence Against	Evidence For
Smelting of ore	Crucible volume not large enough.	None
Remelting and casting of steel	Steel cooled inside the crucible. No evidence of moulds. Crucibles have lids.	None
Decarburization of cast iron by oxidation	Traditional methods require open crucible but Merv crucibles have lids.	Presence of cast iron prills. Al-Jildaki's text.
Decarburization of cast iron by iron oxide	No conclusive evidence for cast iron in Central Asia at this date.	Presence of cast iron prills.
Carburization of wrought/bloomery iron with carbon	None	Known traditional method. Zosimo's text Most economical use of crucible's volume
Mixing of wrought/bloomery iron with cast iron	No conclusive evidence for cast iron in Central Asia at this date. Volume of the crucible is too big.	Presence of cast iron prills. Al-Beruni's text (?)

(see Chapter 3 for discussion of the texts by al-Jildaki, Zosimos, and al-Beruni.)

If plant material was used, is there any evidence suggesting which plants they may have been? Zosimos mentions the use of the skins of the fruits of the palm tree, among other plant materials, which are difficult to translate (see Chapter 3). Archaeobotanical examination of plant remains from the workshop identified wheat, barley, vivieae (pulse), cucumber/melon, watermelon, grape, almond/peach, thick walled nutshell, cotton, prosopis (cat's claw), alhagi (camel thorn) and small seeded legumes (Herrmann *et al.*, 1997, 29-31). Charcoal was also found at Merv including pistachio (*Pistacia*). Chenopodiaceae, Tamarisk (*Tamarix*) and willow/poplar (*Salix/Populus*) elm (*Ulmus*), species of Prunus, members of Pomoideae (apple/pear/hawthorn group), juniper (*Juniperus*), *Ephedra*, mulberry (*Morus*) or *Celtis* (Gale, forthcoming). Theoretically, any of these types of plant matter could have been used in the crucible charge but there is no supporting evidence, such as textual evidence or remains of crucible charge material, which points towards the use of any particular one of these species.

Classical, Islamic and ethnographic accounts mention the addition of other substances into the crucible (see *Chapter 3*). Although fragments of glass and copper alloys were found in the crucible steel site, their composition compared to the crucible slag and the ingot suggested that they were not part of the crucible charge (see *Glass*). The glass was probably from drinking vessels used by the craftsmen in the hot workshop and unintentionally broken.

The varying amount of manganese in the crucible slag suggests that it may have been deliberately added. The first group of slag has around 2% MnO, while the other group has around 10% MnO, suggesting that a manganese containing material was incorporated into the crucible charge. Not surprisingly, prills found in the high manganese slag also had higher amount of manganese (about 0.1% Mn) than prills in the low manganese slag which had around .05% Mn (see *Iron and Steel*). The manganese would increase the steels hardenability and would have also assisted in the formation of a Damascus pattern (see *Chapter 3*).

Alternatively, manganese could have been part of the initial bloomery smelting ore as it is often found in association with iron ores (Rostoker and Bronson, 1990, 99). It is possible that different parts of the ore body contained areas particularly rich in manganese and the different percentages in the slag reflect the use of ores from different areas, or perhaps different ore or iron sources. The fact that the percentage of manganese forms two groups, rather than a continuous range suggests that it was not part of the ore but deliberately added to the crucible charge. No manganese rich substances were identified during the excavation but there is Islamic textual evidence for the deliberate addition of manganese to the crucible charge (see *Chapter 3*).

The temperature that the crucible process reached was a significant question because one of the characteristic features of crucible steel is that the steel was liquid (see *Chapter 4*). The best indicator for the temperature needed for the process is the steel ingot. The preserved part of the ingot has a carbon content of around 1.2-1.4%, indicating that the temperature achieved was indeed *c*.1475 ^{O}C. This is a particularly high temperature for an ancient furnace to reach and maintain for a period of time. The interpretation of the furnace, as comparable to a deep fuel bed furnace, is significant because the temperature reached in the oxidation zone of deep fuel bed furnaces can reach 1600 ^{O} C (Ministry of Power, 1958).

Depending on the size of the furnace, between 6 and 18 crucibles were fired in the furnace at any one time. The time needed to fire the charged crucibles was not determined. According to ethnographic accounts of crucible steel production in India, the time ranges from 1 to 25 hours (Bronson, 1986, 38). In order to better estimate the firing time needed at Merv, a comparison was made with ethnographic account. The process most closely resembling the process at Merv was recorded by Holland in south India (Bronson, 1986, 35-39). The crucibles were smaller, 5 inches long (*c.* 12 cm), but the external diameter, 3 inches (7 cm), is about the same as the Merv crucibles (8 cm). Holland's crucibles were pear-shaped, and made of ordinary clay with rice husks and the furnace design may have been different. Holland reported the firing of a charge consisted of many pieces of iron (Bronson, 1986, 38), similar to the proposed iron charge used at Merv. Holland, (Bronson, 1986, 38), however, reported the use of leaves as the carburizing agent, rather than wood, presumably used at Merv. Holland reported that it took two hours for the metal to become liquid in the hottest part of the furnace (Bronson, 1986, 38). Holland's product is recorded as weighing between 230 – 310 Mg (*sic*). Whether Bronson means milligrams (mg) or metric grams is unclear but probably means metric grams, otherwise it seems to be a very small amount of steel to produce. In addition, assuming that the interior diameter of Holland's crucible was about 5 cm, a 300 g ingot would have been around 2 cm high inside the crucible, a reasonable size. This is about 1/7th of the weight of the ingot produced at Merv. The shortest firing times Bronson (1986, 38) records fall in the category of 1-5 hours. Although more metal was melted at Merv, the furnaces at Merv presumably ran hotter, which would have reduced the time needed. The firing time at Merv was probably closer to five hours, than 1 or 25. After the firing the crucibles were left to slowly cool inside the crucible, indicated by the evidence provided by the crucibles (see *Crucibles*) and the coarse pearlite structure of the ingot (see *Iron and Steel*).

Alternative arguments

There are a number of issues and alternative arguments against the conclusions based on volume calculations. The most obvious argument is that the craftsmen were not necessarily concerned about the height and volume of the crucible. If this were the case, then the above argument of the volume of the charge based on the minimum height is invalid as indication for plant matter as part of the crucible charge.

Besides carbon and hydrogen, plant matter contains some inorganic compounds which remain as ash. Ash typically contains high amounts of CaO (around 30%) and MgO (2-11%) and other elements such as K_2O and SiO_2 (Rostoker and Bronson, 1990, 83). The percentages of these elements differ due to many factors including the particular plant species, the part of the plant and the soil it was grown in. These elements are also present in varying proportions in bloomery slag as a result of the fuel used during smelting. As a result, it is not possible to distinguish in the crucible slag between elements contributed by the charcoal from the smelting to any plant matter added to the crucible charge.

On the interior of many of the crucible fragments, there is a significant quantity of prills attached to the wall and in the slag (see above). The majority of prills are composed of white and grey cast iron, or steel. Prills were also noted in the slag of the Hyderabad crucibles (Lowe, 1989, 241) but virtually none were seen associated with the crucibles the author observed from south India or Sri Lanka. This suggests that the Hyderabad process of mixing cast and wrought iron, and the Merv process are more similar with each other than with the Indian/Sri Lankan processes (see *Chapter 2*).

The cause of the prills is still uncertain and a systematic study of prills from all known crucible steel processes has yet to be undertaken. There are two models concerning the mechanisms that caused the prills to be located on the crucible walls and in the crucible slag. The first model presumes that the prills on the walls are either residual bloomery iron carburised in situ, or they formed in the slag from the reduction of iron oxides initially present in the bloomery slag. Their small size and the presumed sticky nature of the crucible wall and slag during firing prevented the prills from falling off the walls, into the ingot.

The second model presumes that there was a carbon boil, or a similar mechanism causing splashing inside the crucible. A carbon boil occurs during the formation of carbon monoxide from the cast iron when reacting with oxides (Gilchrist, 1989, 347). Oxides would have been introduced into the crucible on the oxidized or weathered surface of any iron placed into the crucible. It is unlikely that cast iron produced inside the crucible would then forcibly react with previously unreacted iron oxide to produce a carbon boil, but the author is not aware of any studies that have examined this possibility. However, any oxides might have already been reduced by the time liquid cast iron is formed. This model also presupposes that prills in the slag were not reduced out of the slag but are from the settling of prills that splashed up out of the slag and are settling through the slag, back to the liquid metal below. Evidence that cast iron may have been part of the crucible charge might be observed in the quantity of cast iron prills on the walls and lids.

Previously, the two types of iron, bloomery and cast iron, needed for the co-fusion process were considered as the most likely charge in the crucible (Feuerbach *et al.*, 1997). This argument was based on the identification of cast iron prills in the slag and the high quantity of prills found on the interior crucible walls, presumably from a "carbon boil". The argument that no cast iron is known from Central Asian contexts during this time is again relevant. Nevertheless, this does not exclude that it was used or known there, particularly when one considers that cast iron was produced in China and extensive trade between China and Central Asia lasted for centuries. Evidence for two different types of iron being used, is known from ethnographic accounts. An ethnographic report from Hyderabad, India, discusses the use of two different types of iron in the crucible charge (see *Chapter 2*). These two materials have been interpreted to be bloomery iron and white cast iron (Allan and Gilmour, 2000, 72). Another ethnographic report, written by Massalski on crucible steel making in Bukhara in the 1840s, reports that the process uses small pieces of wrought iron and white cast iron in the ratio of 1 part cast iron to 3 parts wrought iron (Allan and Gilmour, 2000, 72-73 and 535-539). Assuming the white cast iron had about 4% carbon, the product would be a steel ingot with about 1% carbon. If two different types of iron were used at Merv, the ratio of metal was about 1:1 of wrought iron to cast iron, or roughly 1000 g (1200 g) of bloomery iron would have been added to 1000 g (1200 g) of 3% cast iron, for a 2 kg (2.4 kg) ingot. This process is plausible if one discounts the volume argument above and assuming that cast iron was available.

Conclusion

The results of the investigation of the remains from Merv all suggest a developed crucible steel process. The craftsmen chose a clay which was well suited for withstanding the high temperatures for prolonged periods of time while resisting slag attack from the inside, reactions with the fuel on the exterior, and the weight of the crucible charge/liquid steel pressing against its walls, without failure. The charge could utilize less desirable areas of blooms with a high slag content and transform it to a high quality steel ingot. The extensive reuse of grog, trimming and broken crucibles indicate recycling. The crucible steel process was effective and efficient with a high success rate that is reflected in the low number of failed crucibles or failed crucible products uncovered during the excavation.

Determining conclusively whether a metallic iron-carbon alloy was added to the bloomery iron as part of the crucible charge, or carbonaceous material, or indeed both, is difficult without more research on different types of crucible steel production remains from historic and archaeological contexts. However, considering the volume calculations and the alternative arguments and the lack of replication experiments specifically addressing these points, presently the strongest argument is that the crucible charge consisted of 2 kg (2.4 kg) of bloomery iron broken up into pieces, which took up a volume of around 360 cm^3 (425 cm^3) with room for 410 cm^3 (345 cm^3) of plant matter. Experiment revealed that a handful of material had a volume of roughly 110 cm^3 (327 cm^3 = three handfuls of potato/bloomery iron, 350 = 3 handfuls of wood). Therefore, it is concluded that roughly four handfuls of bloomery iron was placed in the crucible with about four handfuls of wood, or a 1:1 volume ratio.

The presence of phosphorus in the prills and ingot is important to consider because of its effect on the forging properties of the steel. Crucible steel experiments by Verhoeven and Pendray (1992, 210) noted that even low levels of phosphorus in crucible steel cause the ingot to be "hot short" (crack during forging), thus requiring low temperature forging (see *Chapter 3*). Low temperature forging can produce spheroidal cementite in hypereutectic steel, such as that found at Merv. The presence of manganese in some of the prills and the ingot suggest that, if repeatedly forged at low temperatures, a

Damascus pattern would appear if the blades were etched. As etching blades was performed in this region at this time (see Al-Beruni in *Chapter 3*), it is likely that blades produced from ingots produced at Merv, had a Damascus pattern.

Archaeometallurgical Remains from Uzbekistan

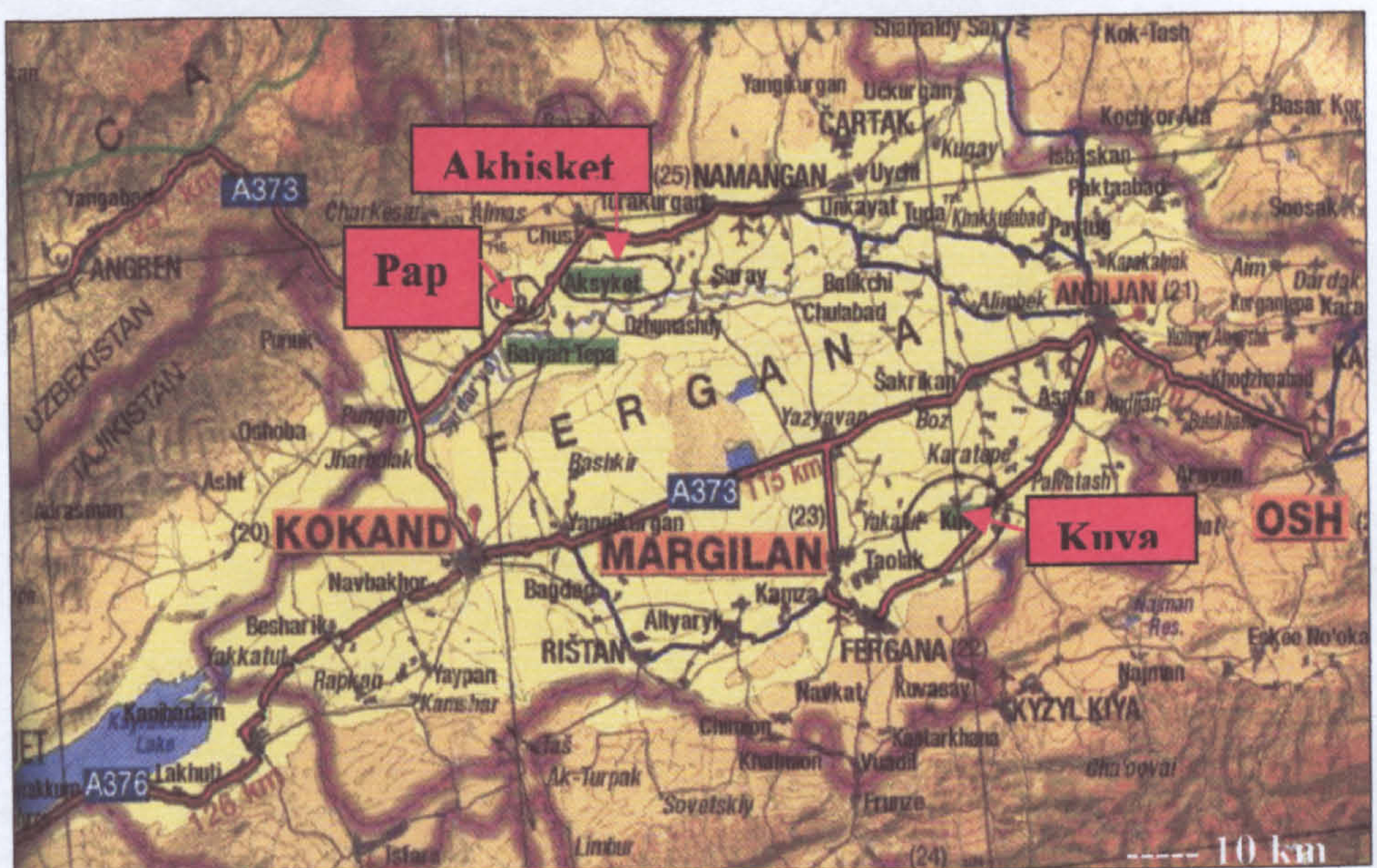
Archaeological remains from the production of crucible steel were discovered in Uzbekistan during the 1960s but were originally identified as glass production remains (Abdurazakov and Bezborodov, 1966). These were re-examined and identified as crucible steel remains by Papachristou (*sic*) and Swertschkow (1993). Papakhristu and Rehren (in press), and Rehren and Papakhristu (2000) have continued to study these remains.

All the fragments studied here are surface finds and the dates are given according to O. Papakhristu (pers. com.) The materials and techniques used for the production of crucible steel in Uzbekistan were compared to those used at Merv. Remains from Akhsiket, Pap, Kuva and Termez were examined using the same methods used to study the remains from Merv. Seven crucible fragments are from a 9th-12th century AD context at Akhsiket, and three are from a 10th-11th century AD context at Pap. Furthermore, a piece of a crucible steel ingot from a 12th-13th century AD context at Termez was also examined. The samples below are labelled with a letter representing the site (e.g. *A* for Akhsiket) followed by an ID number (Appendix J).

Crucible steel production has been reported from an 11th-12th century context at Kuva (Papakhristu and Rehren, in press) and two crucible fragments thought to be from crucible steel production there were also examined. Laboratory analysis, however, indicated that they were from the production of copper-alloys and not crucible steel.

Akhsiket, Pap and Kuva are located in the Fergana valley in eastern Uzbekistan (Maps 8 and 9). Akhsiket and Pap are on the north bank of the Syr Darya River, which flows northwest from the Pamir Mountains. Kuva is located in the south of the valley. The valley is surrounded on three sides by metalliferous mountain ranges and is only readily accessible via the Khodjent "Gates" towards the west. The city of Old Termez is found on the banks of the Amu Darya in the far south of Uzbekistan at the border of Afghanistan.

Map 8: Detail of Central Asia. Area in the red circle detailed in map
(From Rehren and Papakhristu, 2000, 56).



Map 9: Modern Map of Fergana Valley and the cities of Akhsiket, Pap and Kuva. The brown areas at the edges of the map are mountain ranges.
(Cultural Travel Map, 1998).

Akhsiket

Akhsiket is the name given by medieval authors, such as the 10th century Persian geographer who wrote the Hudud al-Alam, to the town containing the hill-fort of Eski Akhsi (Minorsky, 1937, 116). The city was a large political and economic centre for many centuries and excavations indicate that crucible steel was produced from at least the 9th to 12th century AD (Papakhristu and Rehren, in press). This four hundred year period coincides with the beginning of the Islamic incursion into the region and ends with the Mongol invasion around 1220 AD, which virtually destroyed the city and disrupted trade.

Unlike the crucible steel production remains from Merv, the number of crucibles produced at Akhsiket is estimated at well above 100,000 (Rehren and Papakhristu, 2000, 65) testifying to production on an industrial scale. This level of production must have exceeded the demands of the local population and the steel must have been primarily produced for trade. The remains studied so far represent only a small fraction of the entire quantity of remains, yet the results of these investigations have already greatly increased our understanding of the crucible steel process occurring at Akhsiket.

According to Papakhristu and Rehren (in press) three types of crucibles were employed at Akhsiket (Figure 70):

1) "Massive thick-walled ones with vertical or slanting corrugation";
2) "Average wall thickness with fine corrugation";
3) "Thin-walls with vertical or slanting corrugation".

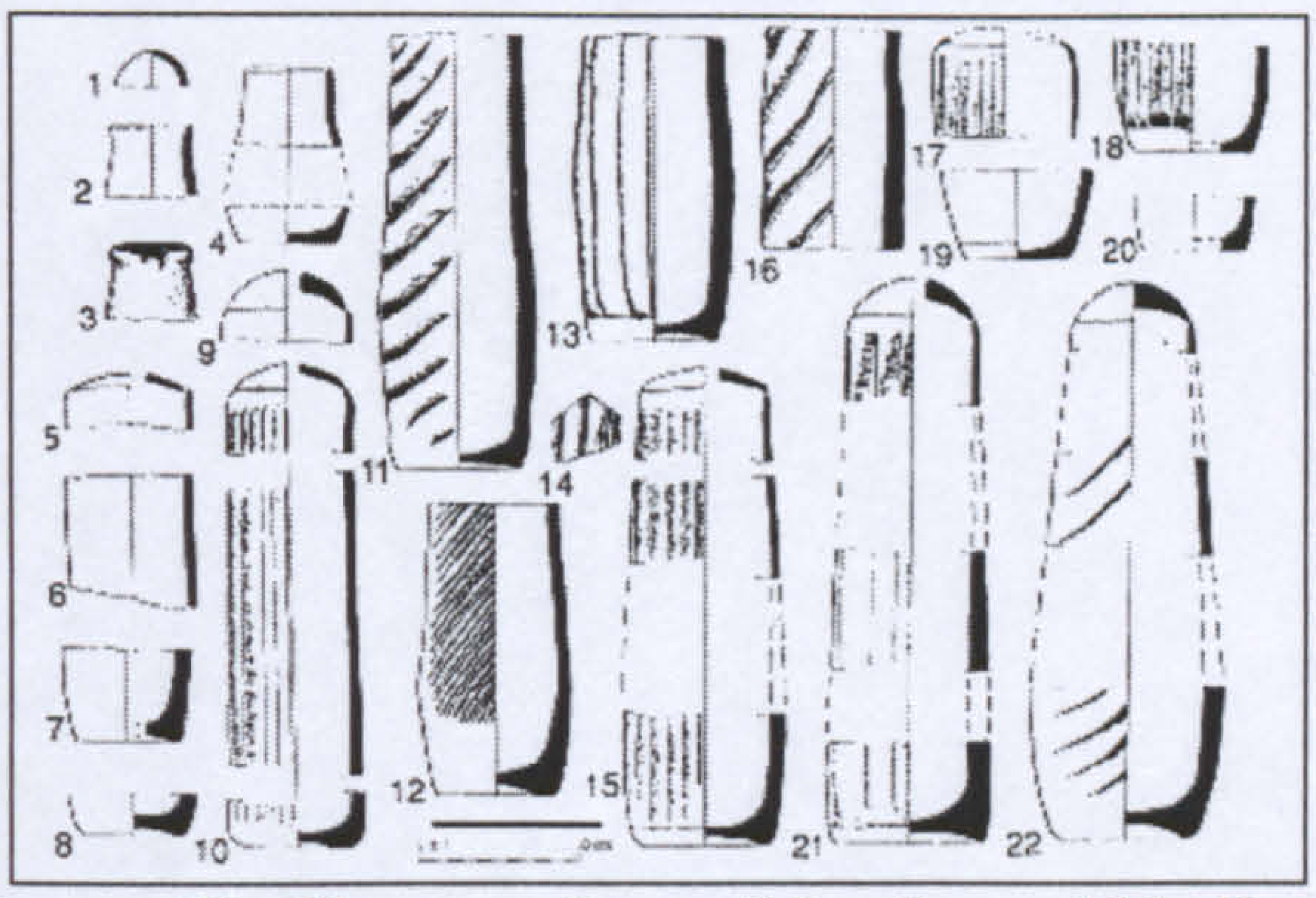


Figure 70: Shapes of crucibles from Akhsiket *(scale 10 cm)*
(From Papachristou (*sic*) and Swertschkow, 1993).

The reports by Papachristou (*sic*) and Swertschkow (1993), Papakhristu and Rehren (in press), and Rehren and Papakhristu (2000) describe the "standard" crucible as tubular, 8-9 cm in diameter and 28 cm high. The lids are hemispherical with one central hole and are luted to the top of the crucible wall (Figure 71) but lids with more holes were also found (Figure 72). The bases' external profiles are flat or slightly arching and the inner surface is hemispherical (Figure 73). The walls' thickness decreases from 15 mm to 10 mm near the base to 8 to 5 mm near the top. The walls' exterior is corrugated and glazed (Figure 74), while the interior exhibits the impression of a woven textile pattern (Figure 75). The interior pattern is thought to have originated during the forming of the crucible with the use of a textile core, possibly filled with sand, upon which the clay was pressed and then scraped to produce the corrugated pattern on the exterior.

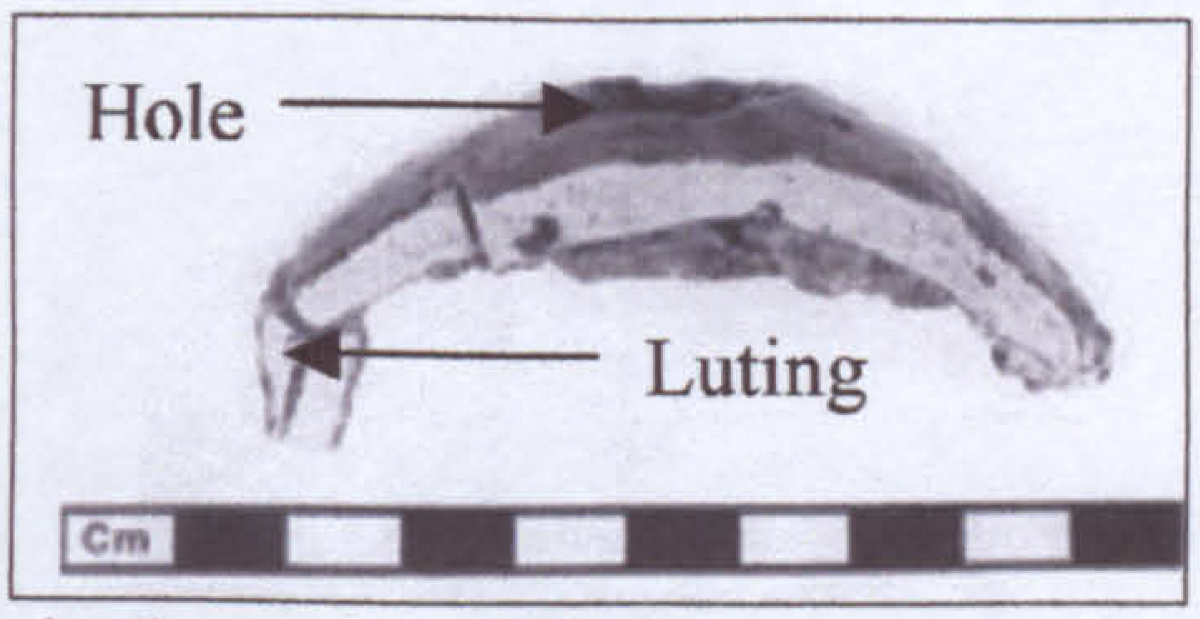


Figure 71: Hemispherical crucible lid with centre hole and evidence of luting. (From Rehren and Papakhristu, 2000, 57).

Figure 72: Lid with three holes (Akhsiket 24). Textile impressions can also been seen on the crucible wall.

Figure 73: Base of crucible. Note that the interior is similar to that of the Merv crucibles but there is no attached pad (From Rehren and Papakhristu, 2000, 57).

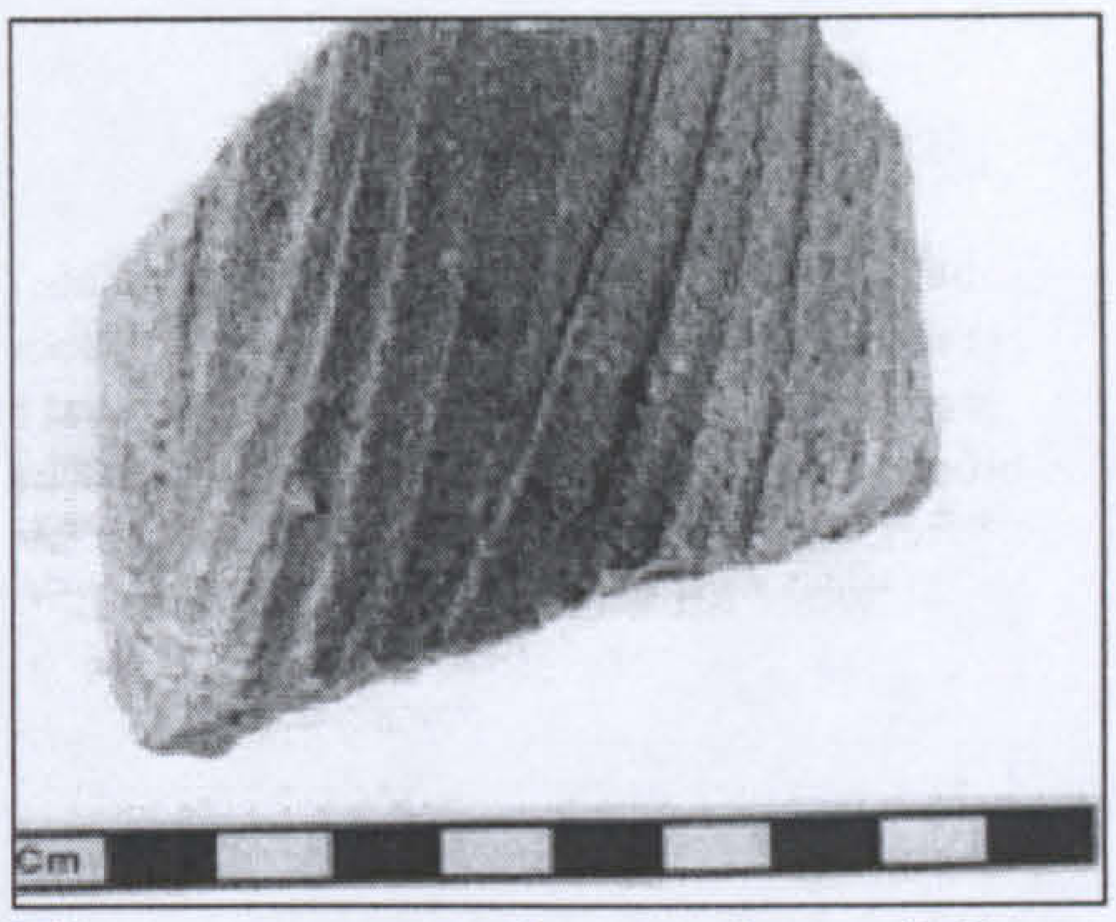


Figure 74: The corrugated exterior of the crucible wall
(From Rehren and Papakhristu, 2000, 57).

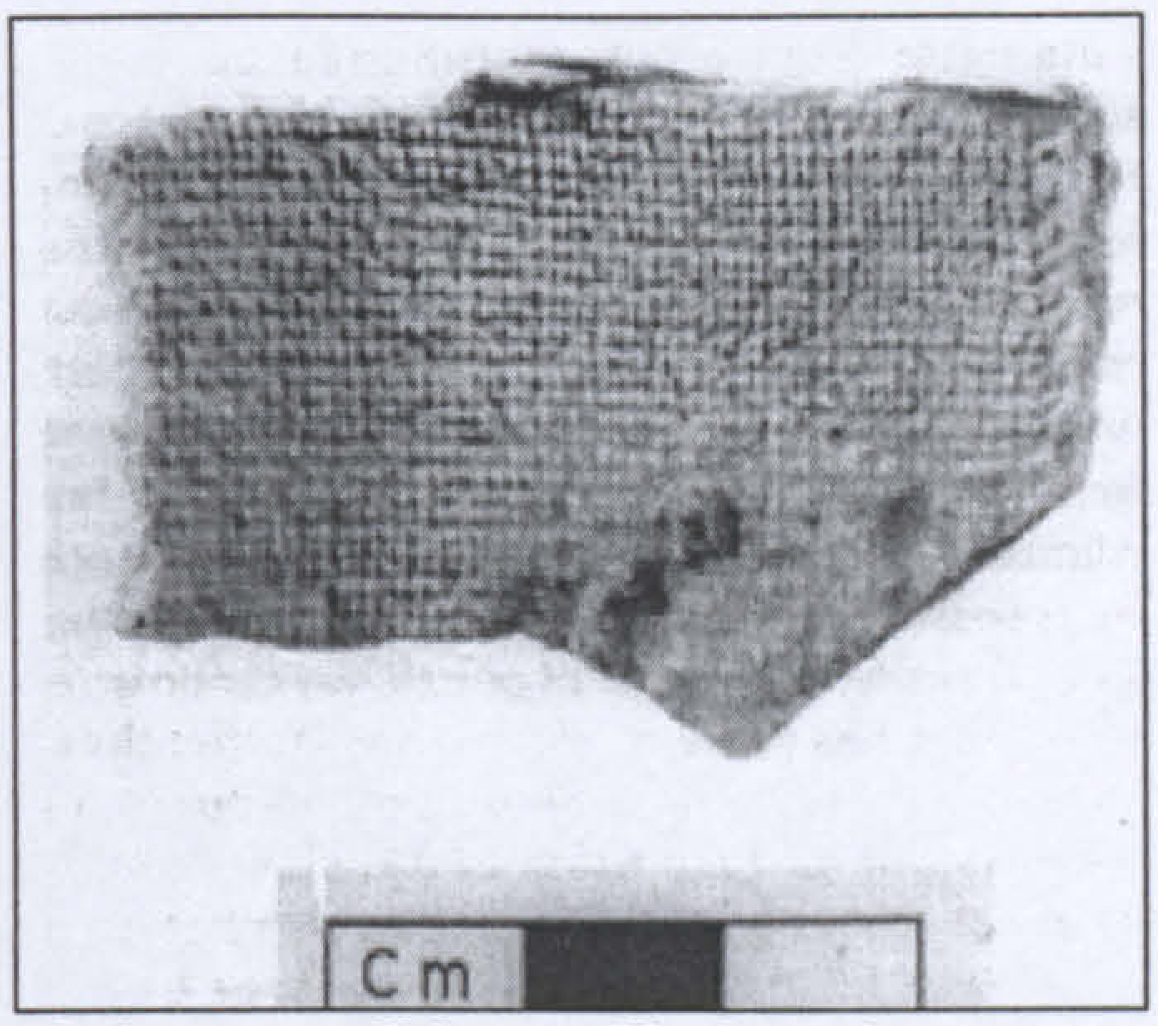


Figure 75: Interior side of the crucible wall showing remains of textile impressions
(From Rehren and Papakhristu, 2000, 58).

Pieces of gravel were found attached to some crucible bases. The gravel may have helped keep the crucibles uniformly heated, assisted in supporting the crucibles to stand upright in the furnace, and allowed the crucibles to be remove with comparative ease after firing (Rehren and Papakhristu 2000, 59; Papakhristu, 1995).

Using textile fabric moulds for the production of ceramics in the Fergana Valley can be traced back to the Bronze Age Chust culture (late 2nd to middle 1st millennium BC; Zadneprovskii, 1962, 321-323 in Papakhristu and Rehren, in press). A mould may have been used because the crucible contained so much temper that it would have been difficult to throw on a wheel. The coarse sand temper would have injured the potter's hands. Papakhristu and Rehren (in press) propose that the craftsmen/potter did not smooth the corrugation probably to help reduce thermal stress during heating.

According to Papakhristu and Rehren's study (in press), the crucibles contain mullite, cristobalite and glass, with a quartz temper, which is almost 50% of the ceramic volume. The elemental composition of a few Akhsiket crucibles was also studied by Papakhristu and Rehren (in press) by ICP to determine the bulk compositions. The results indicated that the crucibles have around a 2:1 ratio of silica to alumina and these two elements added together yield about 95% of the total composition of the matrix. Other elements included FeO (0.5%), TiO_2 (0.7%), with MgO, CaO, K_2O at or below 0.5% and Na_2O at 0.2% (Papakhristu and Rehren, in press). The crucibles exhibit no signs of sagging and could withstand temperatures up to 1650 ^{O}C (Abdurazakov and Bezborodov, 1966).

The crucibles' slag is stated as their most distinctive feature (Rehren and Papakhristu, 2000, 57). The slag is located in the interior of the crucible 15-20 cm above the base, is 2-8 cm thick and over half its volume is composed of vesicular bubbles ranging in size from a few millimetres to 2 cm in diameter (Rehren and Papakhristu, 2000, 57). The appearance of the slag varies and ranges from translucent to opaque. It can be relatively homogenous or contain many inclusions. The colour can be brown, grey, light green, dark green, turquoise, shades of blue or contain areas with all of the above colours.

An initial program of chemical analyses by ICP and SEM-EDS was performed on a few samples by Rehren and Papakhristu (2000, 57-58) to supplement previous analyses reported by Papachristou (*sic*) and Swertschkow (1993). The bulk analyses reported a wide variation in composition presumably due to inclusions of unreacted crucible charge material. The SEM-EDS analysis of inclusion free areas is reported as follows: 60% SiO_2, 20% Al_2O_3, 15% MnO, 1% K_2O, 3% CaO, and 2% FeO (Rehren and Papakhristu, 2000, 58).

Rehren and Papakhristu (2000) have proposed the contents of the crucible charge using mass balance calculations. They concluded that the majority of the iron in the charge came already in the metallic state but a significant part of the iron also arrived as iron oxide. Their strongest hypothesis is the use of raw or partially consolidated bloom in the charge along with charcoal (Rehren and Papakhristu, 2000, 62). The result was a crucible steel ingot weighing around 4.5 kg. This would result in an average annual production of 1100 kg of crucible steel a year for four hundred years (Rehren and Papakhristu, 2000, 65).

More analyses were performed as part of the present study to produce additional data to directly compare the remains from Akhsiket with the crucible steel remains from Merv. The crucible fragments studied from Akhsiket fit the descriptions already reported by Papakhristu and Rehren (in press). The fragments have a white matrix with varying amounts of tiny dark grey specks, which on visual inspection appear to be inclusions, but reveal their true nature as voids under the microscope. *A 12* has no visible voids; *A 16*, *A 20* and *A 23* have some voids; *A 15* and *A 19* have an abundance of voids. A textile pattern can be seen on the interior wall of samples *A 12* and *A 19*. On the interior wall of *A 2* and *A 23* there is a thin layer of glaze, presumably the samples are from the area above the main slag cake, at the top part of the crucible near the lid. A thick layer of slag is observed on samples *A 15*, *A 16*, *A 17*, *A 19*, and *A 20*. On all of the samples corrugation and a glaze was observed on the exterior side of the crucible wall. The glaze ranges from thin (*c.* 1 mm) and either clear with few spots of black glaze (*A 16*, *A 20*, *A 23*) or green (*A 15*) to a thicker (*c.* 3 mm) dark black or brown-green glaze (*A 12*, *A 19*).

Figures 76 and 77: Two examples of the different types of crucible slag found inside the Akhsiket crucibles, Akhsiket 18 (left) and Akhsiket 19 (right).

Thin-sections were made of five crucible fragments; three of these also had slag attached to the wall. Two additional pieces of slag were also examined. EPMA was used to determine the elemental composition of the crucible matrix of seven fragments. EPMA was also used to study pieces of slag, prills, the exterior black glaze and the interior "glaze".

The crucibles were divided into three groups based on their alumina content and silica to alumina ratio, determined by EPMA over 100 μm square area avoiding inclusions and pores (Table 15 and Appendix K):

- Group 1 (A 12 and A 16) has 20% Al_2O_3 (3.5:1)
- Group 2 (A 2, A 15 and A 23) has 27-30% Al_2O_3 (2:1)
- Group 3 (A 17 and A 19) has 36% Al_2O_3 (1.5:1)

The different percentages of alumina and the ratio of silica to alumina suggest the use of at least three different clay sources or large variations within a source. There are also variations in the percentage of minor elements within Groups 1 and 2, particularly in the amount of K_2O in Group 1 (A12 has K_2O 6%), and FeO in A2 (7.5%) in Group 2.

Table 15: Summary of Elemental Composition of Akhsiket Crucibles

	SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	TiO_2	V_2O_5	Total
Group 1										
A 12	70%	20%	6.0%	0.5%	0.3%	0.2%	1.9%	bd	bd	99%
A 16	72%	20%	2.6%	0.3%	0.2%	1.1%	1.2%	0.8%	0.2%	98%
Group 2										
A 2	56%	27%	1.8%	0.2%	0.3%	0.6%	7.5%	0.8%	0.2%	94%
A 15	63%	30%	1.9%	0.1%	0.1%	0.3%	1.5%	0.5%	0.2%	98%
A 23	58%	30%	2.4%	0.1%	0.3%	1.0%	0.5%	0.9%	0.2%	93%
Group 3										
A 17	55%	36%	0.5%	0.2%	0.2%	0.5%	2.2%	0.3%	bd	95%
A 19	55%	36%	1.0%	0.5%	0.4%	0.4%	2.5%	1.0%	0.2%	97%
bd = at or just below detection limit to state the elements presence with confidence.										

These results are not directly comparable to the results reported by Papakhristu and Rehren (in press) because they were using bulk analyses, which incorporated inclusions into the total composition. They reported that silica and alumina totalled 95% of the elemental composition and *c.* 50% of the volume of the crucible fabric being composed of quartz (SiO_2) inclusions, which would account for this higher percentage of silica.

All the fragments are very similar in thin-section. Quartz was used for tempering and comprises around 50% of the total volume of the crucible matrix (Figure 78). Papakhristu and Rehren reported the same percentage (in press). All the quartz has low spherocity and rounded edges. The rounded edges do not appear to be from reaction with the clay matrix, and no reaction zone is visible. The size of the quartz ranges from 100-400 μm. Some of the larger quartz pieces have cracked probably as a result of thermal stresses caused by heating and cooling during the process. Grog was not used.

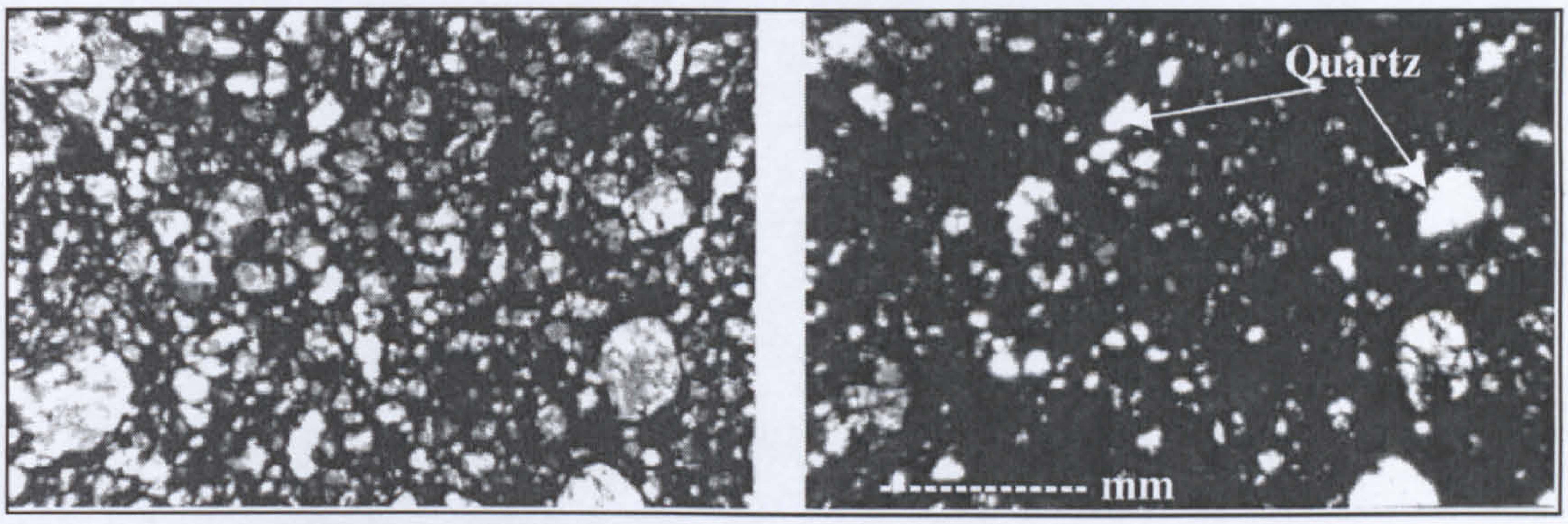


Figure 78: Typical example of the Akhsiket crucible fabric. The photomicrograph is the thin-section of Akhsiket 16, left photo is taken using transmitted polarized light and the right is the same area taken using crossed-polarized light.

The exterior glaze was also analysed (Table 16 and Appendix K) and the results were consistent with those of Rehren and Papakhristu (2000) who analysed the exterior glaze using a JEOL 6400 SEM with EDS. The glaze has a high composition of calcium and potassium, and little iron and manganese oxides. They also reported that the boundary to the ceramic body is more transitional in the glaze than in the slag and this was also observed in these samples.

Table 16: Elemental Composition of Akhsiket Crucibles' Glaze

	SiO_2	Al_2O_3	MnO	K_2O	CaO	Na_2O	MgO	FeO	TiO_2	Total
A 2	51%	13%	0	2.4%	13%	3.0%	1.5%	2.5%	0.3%	87%
A 12	48%	18%	0.1%	2.5%	25%	0.2%	1.3%	1.1%	0.2%	96%
A 15	65%	19%	0	2.6%	6%	0.2%	0.6%	2.4%	0.5%	96%
A 17	56%	28%	0	1.4%	5%	0.5%	0.6%	4.9%	0.5%	97%

The higher percentage of CaO and MgO in certain samples corresponds to the samples with a thicker and darker glaze. The higher percentage of CaO and MgO in the glaze compared to the percentage in the crucible matrix is typical of an ash glaze (Rye, 1981, 46).

The slag from A 19 and particularly A 20 is diachroic. They are blue or green in reflected light and brown in transmitted light. The slag of A 16 is more similar to the Merv slag in appearance, in its glassiness and green colour, but the composition is very different (see below). The slag is also spread over a larger area and has remnants of "bubbles" larger (around 1 cm in size) than the "bubbles" in the Merv slag (0.5 cm). In the two examples examined there is a separation between the slag and crucible wall possibly due to shrinkage.

Table 17: Summary of Elemental Composition of Akhsiket Slag

	SiO_2	Al_2O_3	MnO	K_2O	CaO	Na_2O	MgO	FeO	TiO	Total
A 16	61%	11%	16%	1.0%	7%	0.3%	0.6%	2.4%	0.3%	100%
A 17	56%	10%	20%	0.7%	2%	0.2%	0.3%	1.3%	0.2%	91%
A 18	61%	9%	17%	0.9%	4%	0.2%	0.7%	3.8%	0.3%	97%
A 19	62%	10%	15%	1.1%	7%	0.2%	0.9%	2.7%	0.3%	99%

The slag has a manganese content between 15-20% but little alumina (10%) (Table 17 and Appendix L). The alumina content of the samples reported by Rehren and Papakhristu have almost twice the alumina content (20% compared to 10%), but less CaO (3% compared to 5%). The difference is probably due to the analysis of inclusions during the bulk analyses.

When examined in thin-section the slag shows very little reaction between the slag and the crucible wall. The relatively large percentage of tiny prills trapped in the slag indicates that the slag was quite viscous. The striations with different colours suggest areas of different compositions and a high degree of inhomogeneity. In sample A 17 the slag has regions of interlocking radiating acicular crystal growths (Figure 80).

Figure 79: The exterior appearance of the slag from Akhsiket 17.

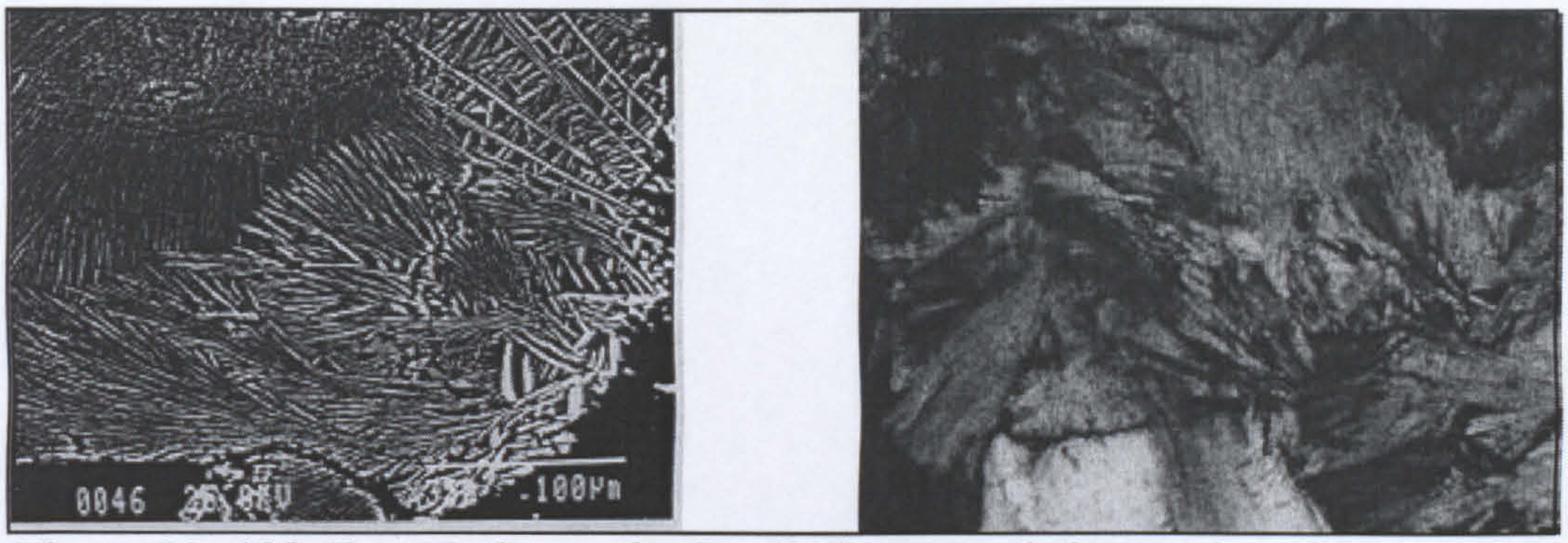


Figure 80: Akhsiket 17 observed using backscattered electron imaging (left) and under transmitted polarized light. Note the dendritic appearance and radiating crystal growths.

Two of the slag samples from Akhsiket containing prills were analysed. The prills were too small to etch and observe their structure by optical microscopy. EPMA revealed the elemental composition presented in Table 18 and Appendix M.

Table 18: Elemental Composition of Akhsiket Prills

ID	Fe	P	Cu	Mn	Total
A 16	98	0	0.1	0.1	97.8
A 19	97	0.1	0	0.1	96.9

As discussed above in relation to the Merv prills, how representative the elemental compositions of prills are compared to the final ingot needs further investigation. However, here it is assumed that the compositions are similar. The presence of phosphorus can affect the way the ingot was forged, i.e. low temperatures would be needed (details of the influence of phosphorous is discussed in chapter 3). The presence of manganese in the prills is particularly significant because potentially manganese can promote the alignment of globular cementite thus producing a Damascus pattern (see chapter 3). Thus, the ingot could potentially have been forged into a blade with a Damascus pattern.

Pap

The ancient hill-fort of Pap (also called Bab and Pab) (Shirinov *et al.*, 1998, 23) is situated approximately 10 km west of Akhsiket. Three crucible fragments were examined from Pap. The fragments are from a similar type of crucible as those from Akhsiket. One fragment (P 10) also exhibits a textile pattern on the interior wall. Sample P 11 had a domed lid attached to a piece of the crucible wall (Figure 81).

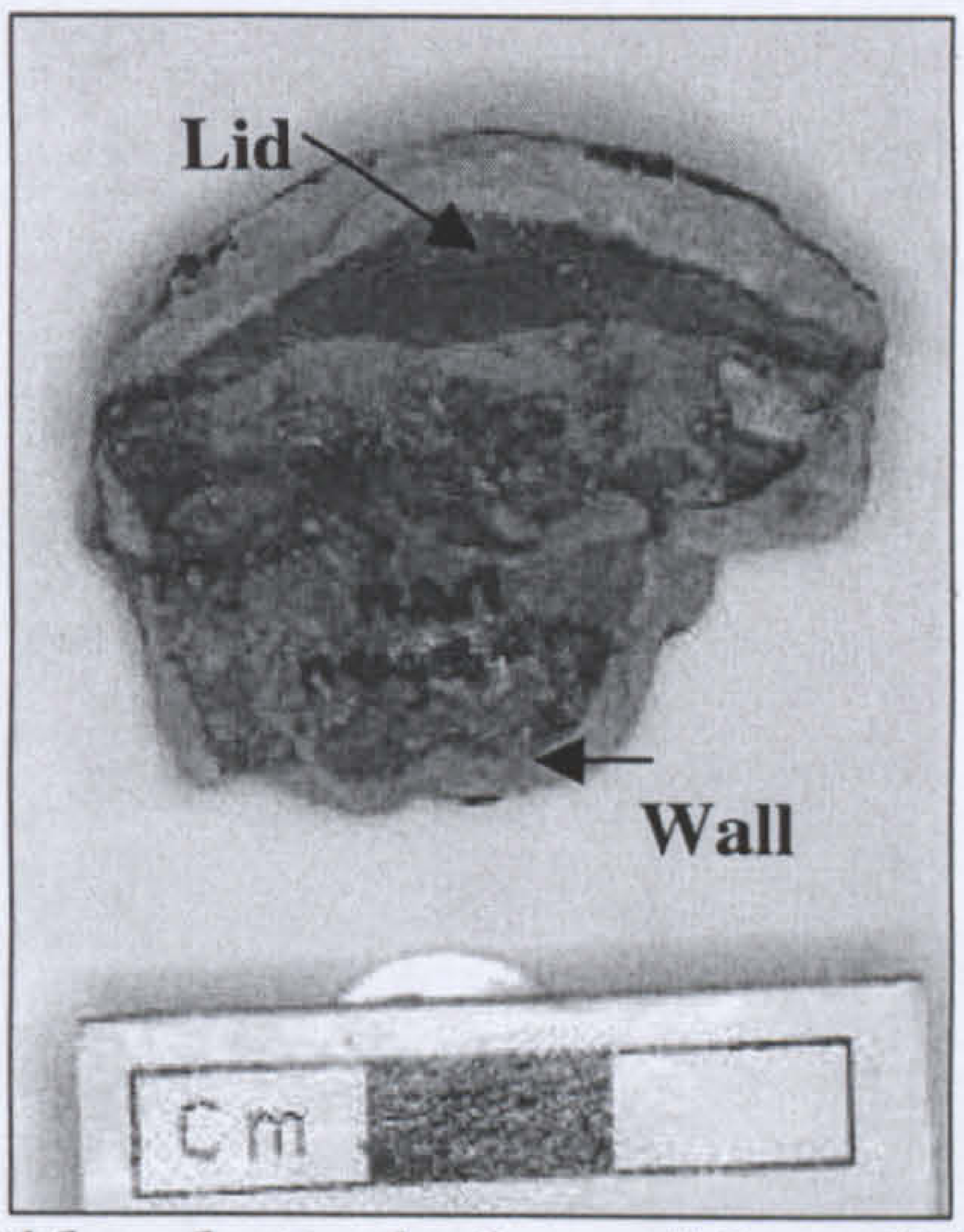


Figure 81: Lid and attached crucible wall from Pap 11.

Figure 82: Impression of a textile on the interior side of the wall of Pap 10 .

Table 19: Elemental Composition of Pap Crucibles

	SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	TiO_2	V_2O_5	Total
P 9	65%	26%	2.0%	0.2%	0.2%	0.5%	1.2%	1.2%	0.3%	97%
P 10	61%	30%	0.9%	0.3%	0.1%	0.5%	0.3%	1.3%	0.3%	95%
P 11	56%	34%	1.0%	0.3%	0.2%	0.7%	1.4%	1.7%	0.4%	96%

All three crucibles were made from the same type of clay. All the samples are similar in composition to the crucible matrix of Akhsiket Group 2, in the percentage of alumina (*c.* 30%) and ratio of silica to alumina (*c.* 2:1). The majority of inclusions are quartz, composing around 50% of the total of the ceramic composition (Figure 83). The quartz is subangular with high spherocity and ranges in size from about 100 – 300 μm in length. Around 2% of the total ceramic is composed of irregular shaped opaque black/brown inclusions with soft edges. The identity of the inclusions has not been determined but the appearance implies iron rich clay areas due to the irregular shape with no definite edges and appearing to merge with the clay matrix.

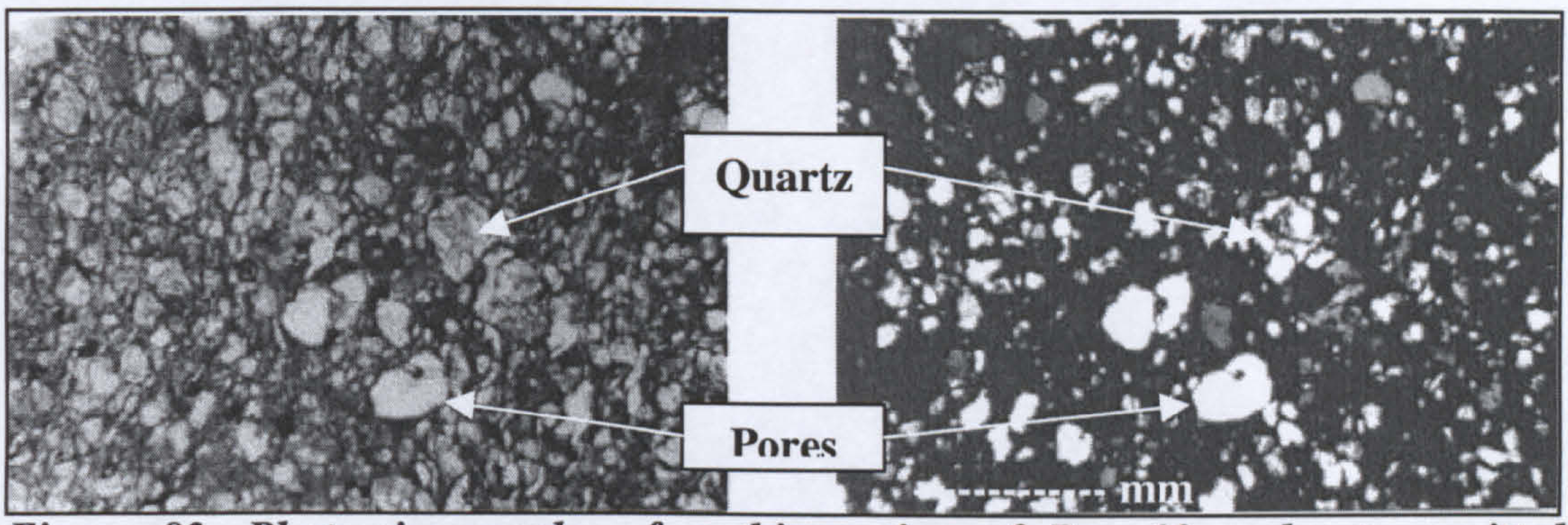


Figure 83: Photomicrographs of a thin-section of Pap 10 under transmitted polarized light (right) and under cross polarized light (left) indicating quartz temper and pores.

The exterior surfaces of the Pap fragments have a thin layer of glaze with a higher percentage of CaO and MgO than the ceramic body indicating an ash glaze (Table 19 and Appendix K).

Table 20: Elemental Composition of Pap Crucibles' Exterior Glaze

	SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	TiO_2	V_2O_5	Total
P 9	66%	15%	2%	8.3%	0.4%	1.1%	3.6%	0.4%	0.1%	97%
P 10	59%	17%	2%	7.6%	0.7%	1.3%	2.8%	0.7%	0.2%	91%
P 11	59%	21%	3%	6.7%	0.6%	0.7%	1.8%	0.5%	0.1%	93%

P 11 has about 3% MnO whereas P 9 and P 10 do not have detectable amounts. Fragments 9 and 10 appear to be from the top part of the crucible and do not contain remains of the thick slag cake. However, there is a thin layer of glaze on the interior.

Table 21: Elemental Composition of Pap Crucibles' Interior Glaze

	SiO_2	Al_2O_3	MnO	K_2O	CaO	MgO	FeO	TiO_2	V_2O_5	Total
P 9	66%	16%	6.4%	2%	1%	0.4%	1.4%	0.9%	0.2%	94%
P 10	63%	16%	7.8%	1%	1%	0.3%	0.7%	0.5%	0.1%	90%

This glaze has a significantly higher percentage of MnO (*c.* 7%) than the percentage that is found in either the crucible matrix or the exterior glaze (3% and below). The low level of CaO and MgO, compared to the exterior glaze, suggests that plant matter (e.g. charcoal) was not a major contributor to the formation of the interior glaze.

<u>Kuva</u>

The ancient city of Kuva, also called Kobo in medieval manuscripts, was located on the Silk Road. Various religions were practiced there including Zoroastrianism and Buddhism, and later Islam (Shirinov *et al.*, 1998, 13). The medieval traveller al-Istakhri (850-934) states that it is the same size as Akhsiket (Shirinov *et al.*, 1998, 25). Furnaces for smelting metal has not been found but crucibles from processing copper and iron have been discovered in various locations within the city (Shirinov *et al.*, 1998, 65).

According to Papakhristu and Rehren (in press), fragments of crucibles used for crucible steel production were found at the hill-fort of Kuva. The two small crucible fragments studied were originally believed to be from crucible steel production because they have the same visual characteristics as crucibles shown to have been used for crucible steel production elsewhere, namely they are about 1 cm thick, composed of a white firing clay, have a black exterior glaze and a slag like material in the interior. During the analysis of the interior slag, a comparatively high percentage of copper oxide (3% and 17%), and the corroded copper-coloured inclusion in the slag, suggested that the crucibles were from copper-alloy processing rather than crucible steel. Only additional investigation of more, and larger crucible fragments will confirm the process for which these crucibles were employed. The two crucible fragments differ slightly from each other in colour: K 3 is lighter beige than K 4 (Figure 84).

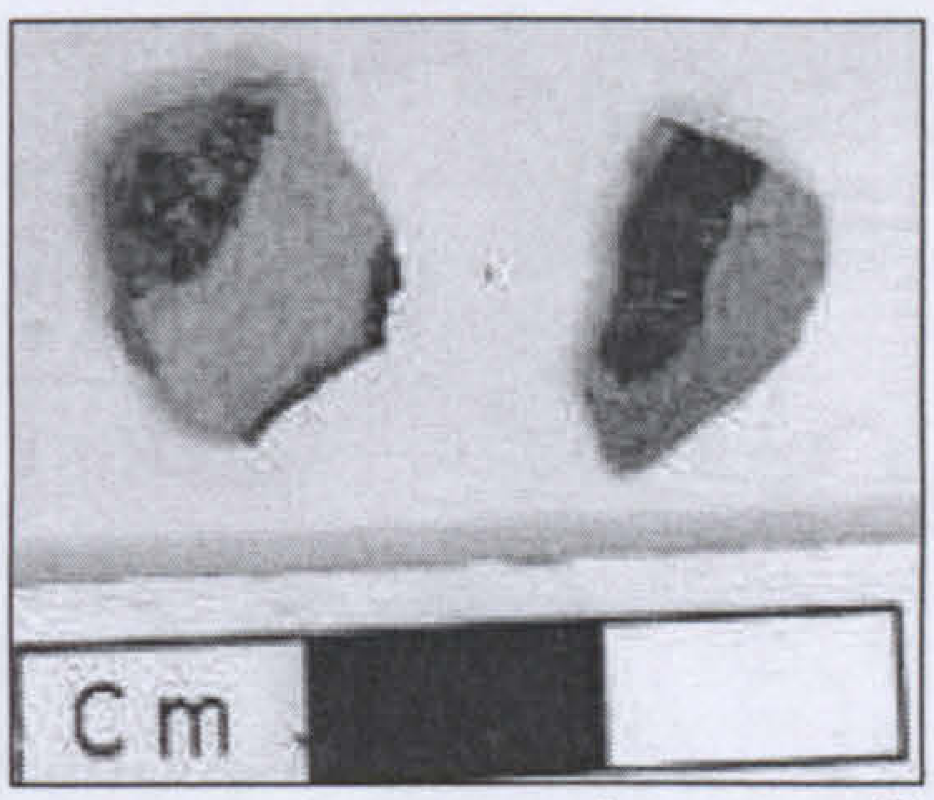


Figure 84: Two copper processing crucible from Kuva.

Table 22: Elemental Composition of the Kuva Crucibles

	SiO_2	Al_2O_3	K_2O	CaO	Na_2O	MgO	FeO	TiO	V_2O_5	Total
K 3	58%	31%	2.6%	1.7%	0.2%	0.8%	2.2%	0.3%	nd	97%
K 4	61%	26%	2.7%	0.4%	0.2%	0.7%	3.6%	0.6%	0.2%	95%
nd= not detected										

The slight difference in colour is probably due to the difference in the percentage of iron in the crucible matrix (2.2 - 3.6% see Table 22 and Appendix K). The clay is similar to the clay used at Pap and Akhsiket Group 2 (alumina *c.* 30%) in that they all have a silica to alumina ratio around 2:1 suggesting the use of a similar type of clay. However, the percentage of iron oxide is higher (*c.* 3%) in the Kuva crucible indicating a different source.

Quartz is the predominant tempering material. It has very low spherocity, is very angular, and comprises about 25% of the volume of the ceramic and range in length from 50 - 400 microns. Opaque black/brown inclusions also appear to compose around 1% of the volume. Well rounded, light brown inclusions of low spherocity were occasionally observed (Figure 85), but their nature has not been studied.

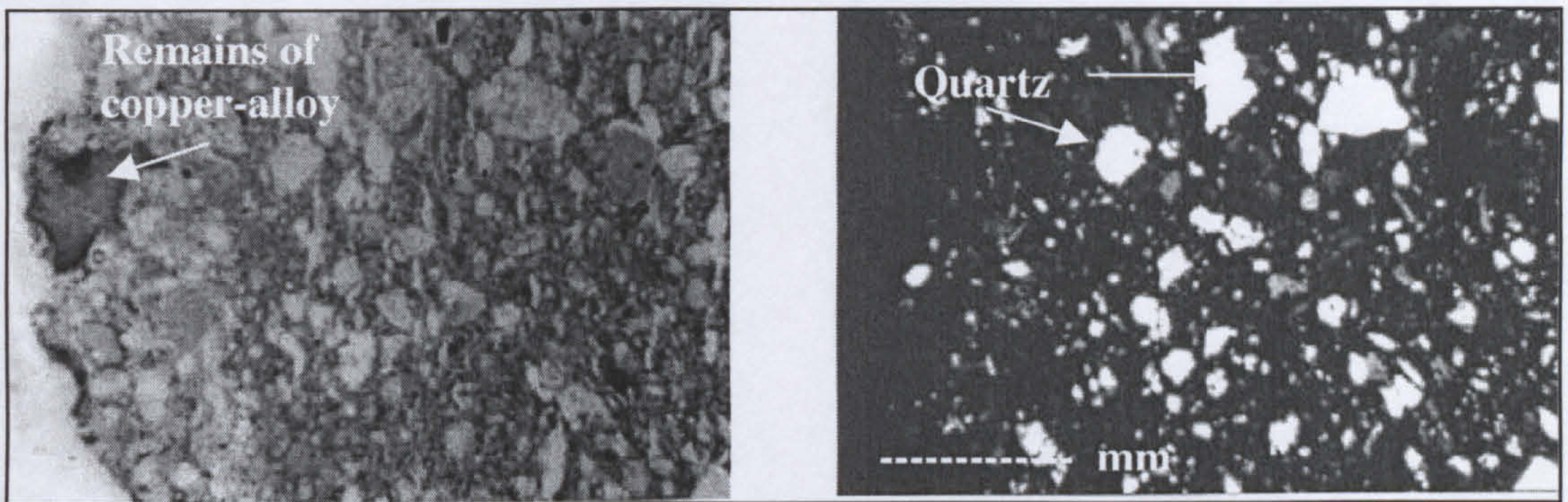


Figure 85: Photomicrographs of a thin-section of Kuva 3 under transmitted polarized light (right) and under cross polarized light (left).

Table 23: Elemental Composition of the Kuva Crucibles' Slag

	SiO_2	Al_2O_3	CuO	K_2O	CaO	Na_2O	MgO	FeO	TiO	Total
K 3	53%	17%	3.2%	4.5%	12 %	1.5%	0.8%	1.5%	0.6%	94%
K 4	43%	9%	17.0%	2.7%	4.7%	0.7%	0.3%	1.8%	0.2%	79%

The percentage of copper in the crucible slag is much higher than would be expected in iron slag (Table 23 and Appendix L). Common alloying elements, such as SnO_2, PbO, ZnO were not analysed for. The analysis of the interior slag suggests that the crucibles were used for copper processing rather than crucible steel. The similarity of the type of clay, white firing, quartz tempered and kaolin-like, to the clay used at Pap and Akhsiket for steel making crucibles is significant because it indicates that this clay was being used for crucible making in general, not only the production of crucible steel.

Termez

Termez is located in the southern region of Uzbekistan at the boarder of Afghanistan. Papakhristu (pers. com) is currently undertaking research into the industrial area.

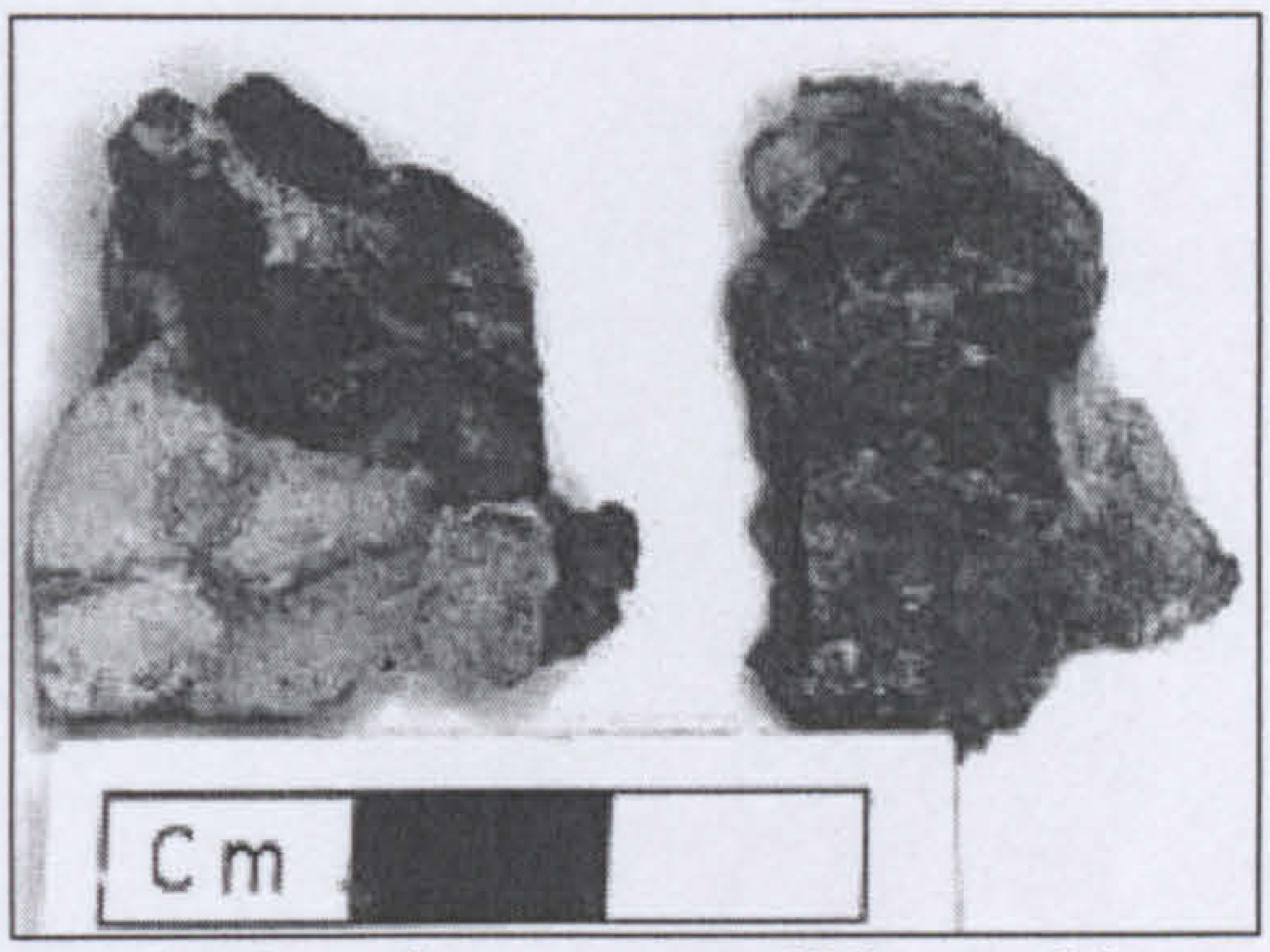


Figure 86: Fragments taken from a crucible steel ingot found at Termez.

A piece of a large egg shaped crucible steel ingot from Termez was available for analysis, courtesy of Papakhristu (Figure 86). The sample was virtually completely corroded, however, using backscattered imaging, it was possible to observe some relic structures preserved in the corrosion products in addition to some uncorroded areas (Figure 87). A similar structure was also found in the crucible steel ingot from Merv. In some places these appear to be cementite needles where in other areas it seems to be proeutectoid cementite outlining the prior austenite grain boundaries. Relic structures of pearlite can be observed between the cementite needles.

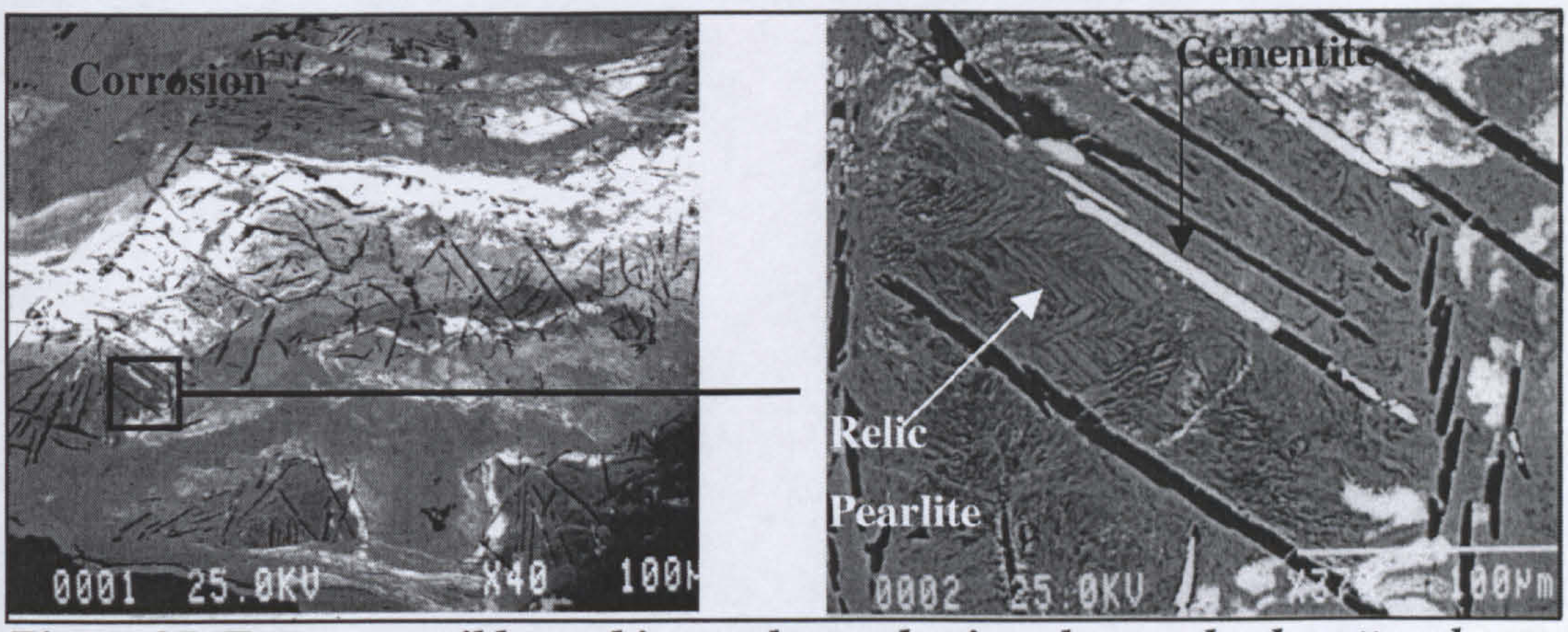


Figure 87: Termez crucible steel ingot observed using electron backscattered imaging.

The presence of pearlite indicates that the ingot was slowly cooled. Some of the remaining cementite needles may be outlining the edges of the prior austenite grain boundaries, as was observed in the Merv ingot. Four spots in uncorroded areas, presumably cementite, were analysed (Table 24 and Appendix M).

Table 24: Elemental Composition of Termez Ingot

	Fe	Cu	Mn	P	Total
1	88	0	0.03	0	88
2	90	0.02	0.03	0.02	91
3	88	0	0.01	0	88
4	91	0.01	0.03	0	91
Elements also analysed for but were not detected were Al, Ca, Si, Ti, Mg, S, Ba, Cr. Au, Ag, As and Ni were at detection limit and may be present. See Appendix M					

The presence of phosphorus and manganese could have affected how the ingot was forged and the appearance of the finished product (see Chapter 3). How much of these and other minor or trace elements were present in the ingot in total, and how it may have affected the forging is uncertain due to the small area preserved and analysed. Nevertheless, the finding of the ingot in a workshop setting indicates that crucible steel was known and used there.

Comparative Analysis

Merv and Uzbekistan Crucible Steel Production

The crucibles from Merv and various sites in Uzbekistan share many common characteristics. They are cylindrical with a diameter *c.* 8- 9 cm and are roughly 20 cm at Merv and 28 cm in Uzbekistan in height. The crucibles have a flat base and were placed on the floor of the furnace. The lids have a hole in the centre and were luted on to the body of the crucible. The clay used is highly refractory and fires to a light grey to white colour. Quartz is used in the crucibles for temper, and the exterior side of the walls has an exterior ash glaze. Local traditional methods were used to shape the crucibles. The crucibles have an interior layer of slag, which has a low percentage of FeO (below 4%). The product was an "egg" shaped ingot composed of slow cooled high carbon steel. The Merv and Termez ingots appeared to have cooled slowly which is significant because the cooling rate can effect the ease of forging and possibly the resulting pattern, if one is present (see Chapter 3-4).

However, there are differences in the materials and process as well. The lids differ in shape; those from Merv are flat while those from Uzbekistan are domed. The Merv crucibles sat on a pad but the Uzbek crucibles did not. The upper areas of the crucible wall and lid of the Uzbek crucibles are not black, but the Merv crucibles are, indicating different furnace design and firing conditions. The crucibles from Uzbekistan are a few centimetres larger than those from Merv. Another difference is the method used to shape the crucible. The Merv crucibles were shaped on a rotating device, whereas the Uzbek crucibles were formed over a mould. The different percentages of elements in the ceramic matrix indicate that the clay came from different sources. Both crucibles have quartz temper but the Uzbek crucibles contain much more (*c.* 50%) compared to those from Merv (*c.* 10%) and the Merv crucibles also contain grog. The exterior glaze is neither as thick nor consistent in colour on the Uzbek crucibles as in the Merv.

The slag is also different. The slag in the interior is much thicker in the Uzbek crucibles and is therefore referred to as a slag cake, rather than a fin. At Merv there are two main groups of slag, a high and a low manganese group. Also the calcium content of the Merv crucibles is much higher (14% - 18% CaO), than the Akhsiket slag (2% - 4% CaO). This suggests that the materials put into the Merv crucible were calcium rich and may suggest freer flowing smelting slag, a different ore source, or different crucible charge. The steel ingots from Akhsiket would have been larger, and almost twice the size of those from Merv. The minor/trace elements present in the Merv and Uzbek prills and crucible steel ingots differ, particularly in the amount of copper. The Merv prills have around 0.3% Cu, while the Uzbek metal has between 0 – 0.1%.

Although there are many differences between the remains from Merv and those from Uzbekistan, the differences are minor; therefore overall the remains are considered to be more similar than different.

Relationship to Stone-paste Ceramics

The composition of crucibles from Merv and Uzbekistan has certain similarities with Islamic stone-paste ceramics. Stone-paste is generally attributed to the Seljuk period (11^{th} –13^{th} century AD) in Iran and Syria. Carved and moulded whitewares are considered to be the earliest stone-paste (Morgan, 1994, 156). The carved ones have a black slip "Silhouette wares" which was carved to reveal the white body underneath.

The development of stone-paste is an important issue in the study of the history of ceramic technology (Mason and Tite, 1994, 78) but the origin is controversial (Morgan, 1994, 155). Typical stone-paste is made of eight to ten parts quartz, one part crushed glass, and one part clay, producing a ceramic with over 60% inclusions (Mason, 1994, 307-308). Historical accounts and ethnographic studies provide insight into the process. Quartz or flint was collected, crushed, sieved and sorted for quality (Mason, 1994, 309-310). The temper was mixed with clay, which acted as a binder. The high percentage of quartz temper would make using a mould necessary because the high percentage of inclusions would have made throwing the clay difficult, particularly because the crushed quartz and glass would have sharp edges that may have cut the potters hands. The final ceramic product has a white, lustrous appearance.

Currently there are five suggestions proposing the origin of stone-paste. The first two point to Egypt. The first is stone-paste was developed in Egypt after Iraqi potters were sent there to make pots and the potters needed to adapt their methods and techniques because of new raw materials (Mason and Tite, 1994, 77-91). The second is that in Egypt the technology was transferred from frit beads or faience to ceramics. These suggestions are based on the fact that the earliest known evidence of stone-paste is a shard from Egypt, dated to 1110-1115 AD (Morgan, 1994, 155). Stone-paste appears to arrive in Syria and Iran after the destruction of the Fustat (Egypt) potters quarters in 1168 AD. It is their presumption that stone-paste technology then travelled to Syria and Iran by the displaced Egyptian potters (Morgan, 1994, 155). Egypt as the source is becoming less likely as more stone-paste ceramics are uncovered from Iranian contexts.

The earliest three securely dated examples of stone-paste are from 12th century Iran (Morgan, 1994, 155). This supports the third suggestion that stone-paste developed out of existing pottery traditions. Quartz was added to earthenware bodies as temper and glass was added to Abbasid opaque white-glazed ware (Morgan, 1994, 155).

A fourth suggestion is that stone-paste developed out of Iranian glass making traditions (Morgan, 1994, 155). This was first proposed by Allan (1973) as one possible precursor to frit ware (stone-paste). Morgan (1994, 155) also puts forward this suggestion and bases his argument on textual evidence cited from Allan (1973). He refers to descriptions of pottery attributed to the *Risalah* of Abu Dulaf in AD 950 and compiled by Yaqut (1179-1225). The text discusses places where imitation Chinese ceramics were made. One place, called Kuslam, attributed to either north-west India or Sind, and the other is Fars where the ceramics are made "...from quartz stone, tin oxide and glass, pounded into a paste, and is inflated (blown)...."(Morgan, 1994, 155; Allan, 1973, 172). The use of quartz, tin-oxide, and glass, and no mention of clay, as Allan points out (Allan, 1973, 172) does suggest the production of imitation Chinese ceramics in glass. Al-Beruni discusses a material made of very similar ingredients to this called Mina (Said, 1989, 193). As quartz is an important constituent to glass production and glass production is a very different method of production than those used for stoneware, this author feels that the argument for the influence of glass-making does not support a "new" development on the road to stone-paste wares.

Scholars appear to have ignored Al-Beruni's discussion of mina and porcelain. He describes the materials and the procedure needed to produce porcelain, which is similar to Mina but he puts them under different headings, indicating that he feels they are different materials. He describes the use of clay mixed with crushed flint and the lime of calcined tin (Said, 1989, 194-195). He then says that goblets made from it are like glass and if the break they are melted and recast, which is not characteristic of a ceramic but glass.

Mason and Tite (1994, 88) briefly suggest that stone-paste prototypes might be found in industrial contexts. The crucibles from crucible steel production in Central Asia may be this evidence. An argument can be made that the materials and technology used to produce the crucibles played a significant role as a possible forerunner of stone-paste. The use of a white firing clay, clear and clean quartz as temper, the crushing, sieving and sorting of the temper, the natural "lustre" of the crucibles seen in the high fired bases, are all features also associated with stone-paste ceramics as well as the crucibles from Merv and Uzbekistan.

The crucibles from Uzbekistan have even more similarities to stone-paste ceramics. The majority of Uzbek crucibles have a high percentage of quartz, upwards of around 50%, which is close to that of stone-paste. The crucibles and the stone-paste are made of a white firing clay matrix and both were shaped using a mould and have an exterior glaze. The stone-paste glazes, however, were deliberately produced. The exterior glaze on the crucible, which ranges from clear, to greens or black, may have inspired potters to produce glazed stone-paste wares.

According to Morgan (1994, 155), Michael Roger's survey of Soviet archaeological literature suggests that moulded monochrome stone-paste ware were produced at Nishapur, Samarkand, and Merv. Al-Beruni also states that stone-paste was produced in Afghanistan and these were made with quartz pebbles. Mason and Tite (1994, 88-89), propose that proto-stone-paste and true stone-paste developed because of problems associated with the availability and cost of raw materials and indeed these problems also occurred at Merv.

Clearly the origins of stone-paste are complex. There is a need for further investigations of the elemental composition of the matrix of stone-paste from sites where contemporary crucibles from crucible steel production were also found. The possibility that these industrial ceramics influenced the development of stone-paste cannot be ignored.

Chapter 2: Comparative Study of Crucible Steel Terms and Processes

"Everything is mine", said gold;
"Everything is mine", said crucible steel;
"I can buy anything", said gold;
"I can acquire anything", said crucible steel.
(Pushkin, 1827)

Islamic and other historical texts contain cryptic clues to the production of crucible steel and related materials. Traditionally scholars have translated metallurgical texts by placing the words in question into one of three classes: iron, steel or cast iron. Considering ferrous products in this manner is a Western/European concept, illustrated by the table of contents in many textbooks on ferrous metallurgy. In reality, however, the only difference in ferrous products is the percentage of carbon. The carbon affects the microstructures and the microstructure affects the metal's properties. Although the difference in working properties was realised early in the history of iron metallurgy illustrated by the use of specific terms (see below), the cause of the different properties as the result of the carbon content was not understood until the late 18^{th} (Smith, 1981, 33). Therefore, to better understand alternative perceptions of ferrous products, such as those which may have been considered in other parts of the world during other times, one must abandon the traditional "Western" categories, while keeping in mind the properties of iron/steel with different percentages of carbon, their individual properties and responses to heat treatments. Reviewing metallurgical terms associated with crucible steel production after examining archaeological remains from its production can shed light on the meaning of terms that have not been conclusively translated by comparing the description of the term to the characteristics of the archaeometallurgical remains identified.

Central Asian Crucible Steel Production

The characteristics of the physical remains of crucible steel production in Central Asia, based on the results discussed in Chapter 1 are presented in Tables 25 and 26. The remains of crucible steel production from Merv and Uzbekistan share many common characteristics. They are, however, not the same process. The physical characteristics of the crucible steel process used in Central Asia, based on archaeological remains, are made of refractory clay with quartz temper. The crucibles sat on the furnace floor and gravel like material was placed on the floor in between the crucibles. The nature of the crucible charge is uncertain but the best hypothesis is bloomery iron and plant matter, possibly with some manganese added. The crucibles were fired until the steel was liquid and then left to slowly cool inside the furnace. The result was a high carbon steel ingot virtually free from slag and non-metallic impurities. These are some of the physical and technological characteristics, which can, therefore, be used to define the characteristics of Central Asian crucible steel production.

Table 25: Characteristics of Central Asian Crucibles

Location / *Characteristics*		Merv	Akhsiket	Pap	Termez	*Common Characteristics*
Fabric	Clay	White firing Kaolin-like	White firing Kaolin-like	White firing Kaolin-like	White firing Kaolin-like	**White Firing Kaolin-like**
	Temper	Quartz Grog	Quartz	Quartz	Quartz	**Quartz**
Form	Shape	Cylindrical	Varies but Cylindrical	Cylindrical	Cylindrical	**Cylindrical**
	Base	Flat	Flat	*NA*	Flat	**Flat**
	Lid Luted Holes	Flat Luted Single centred	Domed Luted	Domed Luted At least 3 holes in one example	*NA*	**Luted Holes**
	Height	~ 18 -20 cm	~25-30 cm	*NA*	*NA*	**~ 20 - 30 cm**
	Diameter	8 cm	~ 8 – 9 cm	~ 8 - 9 cm	Similar	**~ 8 cm**

Table 26: Selected Ingot, Slag and Furnace Features

Location / *Characteristics*		Merv	Akhsiket	Termez	*Common Characteristics*
Ingot	Shape	Egg	Elongated egg	Elongated egg	**Egg shaped**
	Size	8 -10 cm x 7 cm diameter	15-17 cm x 8 cm diameter	15-17 cm x 8 cm diameter based on corroded sample	**~10-15 cm x ~7.5 cm diameter**
	Weight	~2 Kg	~ 4.5 Kg	~ 2- 3 Kg	**~2-4.5 Kg**
Composition	C %	Hypereutectoid Steel	Hypereutectoid steel	Hypereutectoid steel	**Hypereutectoid steel**
	Cooling Rate	Slowly	*NA*	Slowly	**Slowly cooled ingot**
Slag	Shape	Fin	Cake	*NA*	**Fin or Cake**
Furnace	Floor	Broken crucibles	Gravel	*NA*	**Floor materials attached to the bottom of crucible**
	Position of crucibles	Sat on furnace floor	Sat on furnace floor	*NA*	**Crucibles sat on furnace floor**

NA stands for no information available.

Iron and Steel Terms Associated with Central Asian Crucible Steel

Now that archaeological debris from crucible steel production in Central Asia has been studied in some detail, the translations of Islamic texts can be re-examined to ascertain how the translations of the texts compare with the information provided by the analysis of archaeological remains. Evidently the Islamic writers knew of the works of earlier writers, for example al-Beruni refers to al-Kindi and his Book of Swords (Said, 1989, 219). This presents a potential problem because it is difficult to determine if the descriptions are primarily based on first hand observations or partially, or even fully, based on an earlier writing. The content of each text is not reproduced here primarily because Allan and Gilmour (2000) have recently considered them in great detail and it is beyond the scope of this dissertation to compare each of the slight variations in the translations provided by different scholars. However, common themes occurring in the texts and the generally accepted translations of certain terms are presented.

Al-Kindi states that there are two main divisions of iron: the natural and not-natural (Zaki, 1953, 367). Al-Hassan (1978) and Allan and Gilmour (2000) agree that this is more accurately translated as mined and manufactured. It may be argued that "mined" should be understood as "as smelted" and "manufactured" refers to a secondary process (see below). Al-Kindi's further description of "natural/mined" iron is divided into "narmahan" and "shaburqan". Al-Kindi and al-Beruni state the properties of narmahan as female, on account of it being soft (Zaki, 1953, 366), and cannot be quenched (Allan and Gilmour, 2000, 56). These are the characteristics of low carbon iron, commonly called bloomery or wrought iron and this interpretation has been noted by al-Hassan and Hill (1986, 252), Allan and Gilmour (2000, 56), and others.

The second "natural" product is shaburqan (or shabarqan). Shaburqan is stated as being male because it is hard and dark (Zaki, 1953, 366). It is malleable but refuses to be folded (Said, 1989, 213) and is able to be quenched during forging (Allan and Gilmour, 2000, 56). These are the properties of steel and the translation of shaburqan as steel (or hard iron) was noted by Allan and Gilmour (2000, 56). It has also been suggested that it may be cast iron (Allan and Gilmour, 2000, 56) or meteoric steel (al-Hassan and Hill, 1986, 252).

Allan and Gilmour (2000, 56) state that Al-Kindi provides accompanying descriptions suggesting that shaburqan sometimes means cast iron. Evidence that shaburqan meant steel and not cast iron can be found in the writings of Al-Beruni, who states that swords from Rome (Byzantium), Saqalibah (Slavs) and Rus (the area to the north and between the Black Sea and Caspian Sea) are made of shaburqan. Furthermore, Al-Beruni states that swords can be made out of a mixture of shaburqan and narmahan. He states that the Rus "swords have stripes in the middle of soft iron" (Said, 1989, 218), and indeed Russian swords from archaeological contexts confirmed that swords associated with the area known as Rus, are made of steel (see Chapter 4), and were often piled with softer (wrought) iron. One argument against shaburqan being steel is founded in the common notion that steel was not a directly smelted product, however, depending on the furnace design it is possible. Directly smelted steel has been found from a number of archaeological contexts (see Chapter 3). Furthermore, al-Beruni states that shaburqan is a natural type of pulad (Said, 1989, 216), i.e. crucible steel; therefore, it is likely that shaburqan is directly smelted steel or the steely part of a bloom.

Above it was discussed that narmahan is low carbon iron (e.g. bloomery or wrought iron), and shaburqan is steel. Both can be smelted products, therefore, the translation may be "natural" or "mined" iron, but it should be understood as the "smelted " product. Under al-Kindi's second category, not-mined or manufactured iron, falls the product pulad. Al-Kindi clearly states, "Iron which is not natural is steel or *fuladh* (pulad). It means the refined or purified. It is made of natural iron by adding to it while smelting some (ingredients) for purifying it, and for decreasing its softness, until it becomes strong, flexible, susceptible to heat treatments, and until its *firind* (pattern) appears" (Al-Hassan, 1978).

In Central Asia the term pulad is always used to denote crucible steel. The word pulad can be traced back to the Avesta, the sacred book of the Zoroastrians (Allan and Gilmour, 2000, 7). Pulad was considered to be the metal of gods, kings and heroes (Allan and Gilmour, 2000, 7). Traditionally priests passed down the Avesta orally, and all known manuscripts go back to a base manuscript from the 8^{th} –9^{th} century AD (Wiesehöfer, 1996, 95) so the Avesta can not be used to date the antiquity of the word. A variation of the word pulad also appears in an original Manichean Middle Persian (pwl'wd), magical text from Chinese Turkistan (Henning, 1947). The text reportedly gives protection against evil spirits and refers to seven daggers of pulad (Henning, 1947). Although the text is thought to be original, Henning does not propose a date for its production. However, in the 6th century AD Sogdian became the language of the Manichean church in the east (Gignoux and Litvinsky, 1996, 417), therefore we can assume that the text was written before this time, making this text the earliest literary evidence for the term pulad. Variations of the word pulad can be found in New Persian (polad or pulad), Mongol (bolat), Russian (bulat), as well as in Tibetan, Armenian (p'otovat'), Ossetic, Grusinian (poladi), Ukranian (bulat), Chechnian (bolat), Turkish, and Modern Arabic (fūlād) (Toussaint, pers. com.; Abaev, 1985, 265). Additionally, "in Urdu the word is farlād for steel. But in Hindi itself the word exists as phaulad meaning steel " (Toussaint, pers. com.). Detailed research into the etymology of the word pulad is wanting.

Abaev (1985, 265), during his search for the history of the Russian word bulat, proposed that the word may have come from Sanskrit. It can now be argued that the word does indeed come from Sanskrit or one of the many Sanskrit related languages. The word pulad can be viewed as the conjunction of two words *pu* (also transliterated as fu, phu) and *lad* (or ladh). In Sanskrit pu means cleaning or purifying (Cologne Digital Sanskrit Lexicon, 2001). There is no direct translation of *lad* or *ladh*, however, there are over a hundred words for iron in the various Indo-Aryan branch dialects that use variations of the word lōhā, including lauha (see Grierson, 1928, 77). The similarity between pu-lauha meaning purified iron, and pulad, meaning refined or purified steel should not be overlooked and strongly suggests a possible etymological origin for the word pulad. It should not be assumed that the word originated in Sanskrit proper. The Avestan language of Central Asia was very similar to Sanskrit and the possible forerunner of the word may equally be found there or in one of the languages which has a similar root.

Al-Beruni clearly describes a crucible steel process and calls the product pulad. The text also states that objects made of pulad produce a pattern that, by the description, appears to be that of Damascus steel. It is also the earliest reference to the pattern appearing on Indian and non-Indian blades and that the swords are etched to bring out the pattern. A further discussion of pulad from the late 12th century Egypt by al-Tarsusi who recorded numerous recipes (Allan and Gilmour, 2000, 63-64; Al-Hassan, 1978, 39). These recipes and others are presented in Table 27. The approximate weight in grams was calculated from Allan and Gilmour (2000, 64): roughly 1 mann = 150 g, 1 rotl (ratl) = 300g, 1 uqiya = 25 g, and 1 dirham = 2 g.

Table 27: Crucible Steel Recipes from Historical Texts

Writer	Iron	Carbon	Other
Zosimos	4 pounds soft iron (1.8 kg)	Fifteen parts by weight of fruit of the palm called elileg Four parts by weight of belileg	2 parts glass makers magnesia
Al-Beruni (al-dimasqui's)	five ratls (1.5 kg) of horseshoes and their nails, which are made of narmahan	Weight of ten dirhams (20 g) of *rushkhtaj*, A forty dirhams (80 g) bundle of ihlilaj (myrobalan), pomegranate rinds, salt (used in dough), and oyster shells in equal proportions	Golden marcasite stone (pyrite) Antimony Brittle magnesia. Narmahan's liquor (dus?)
Al-Beruni's additional recipes	Narmahan and its water	———	———
	Red sand	———	Borax
Jabbir al-Hayyan	Iron bars (possibly cast iron)	———	Glass, oil, and alkali
Al–Tarsussi	1 rotl narmahan (300 g) ½ rotl shabarqan (150 g)	Handful of acid pomegranate bark	Five dirhams (10 g) of magnesia
	Narmaham (old nails)	17 dirhams (34 g) of myrobalan 17 dirhams (34 g) of belleric	1.5 dirhams (3 g) of magnesia
	1 mann (150 g) of soft iron filings	1 part rue (5 g) 1 part gall nuts (5 g) 1 part acorns (or almond) 1 part aloes (5 g) 1 part cantharides (5 g) to equal 2 uqiya (25 g)	1 part magnesia (8.3 g) 1 part coral (8.3 g) 1 part borax (8.3 g) to equal 2 uqiya (25 g)
	3 ratls (900 g) of shaburqan	20 dirhams (40 g) Myrobalan 5 dirhams (10 g) scammony	7 dirhams (14 g) magnesia
	1 part narmahan 1 part shaburqan (both broken into small pieces)	2 dirhams (4 g) myrobalan seeds Handful of sifted orange peal White of an egg	1 dirhams (2 g) magnesia 5 dirhams (10 g) andarani salt 8 dirhams (16 g) nitrate of Khurasan
Massalski Before 1840	Worked iron White cast iron	(from the white cast iron)	Silver

These Islamic texts provide evidence for the production of pulad including the crucible charges and some of pulad's characteristics including that pulad is made by adding ingredients to natural (smelted) iron. In one of the "recipes, al-Beruni discusses the mixing of narharam and its liquid (dūs or dawsa). Al-Beruni states that dūs (Persian astah) is a sub-species of narmahan. "In Zabulistan it is designated as raw, since it comes out quickly and flows even more quickly than iron. It is hard, white and inclined to be silvery" (Said, 1989, 213). Why would cast iron be a sub-species of narmahan, when its properties are opposite? The association of dūs with narmahan (bloomery iron) and the property that it flows quickly suggests that it is indeed slag. However, as suggested by Allan and Gilmour (2000) and others (e.g Al-Hassan and Hill, 1986, 254), the properties of dūs being hard, white and silvery initially suggests white cast iron.

There is no accepted translation for dūs. The word, however, is found in association with other words in Sanskrit and perhaps there is a relationship between these words and the ancient meaning of the term. Dūs is used as a prefix to nouns, verbs or adverbs implying "evil, bad, difficult, hard, inferior, defiled", or perhaps more importantly, "to be impure" (Cologne Digital Sanskrit Lexicon, 2001). Further supporting the argument, that dūs is slag rather than cast iron, are the words for the latter in Sanskrit including *kAntalauha* and *sekima* (Cologne Digital Sanskrit Lexicon, 2001). Although this has not been investigated, dūs might be etymologically related to dross, the slag that forms on top of copper that is refined in a crucible.

From a process point of view, experiments performed by Verhoeven (see Chapter 3) indicated that slag was a beneficial factor in the crucible steel process because ingots produced without a slag covering cracked during forging (Verhoeven, pers. com.). In addition, during Voysey's (1832) ethnographic observations of crucible steel production in Hyderabad, he recorded the addition of slag into crucibles (see below). Therefore, slag has been used in at least one traditional crucible steel process, it appears to be a beneficial addition to the charge, and Sanskrit words which contain dūs as a prefix mean something impure, thus, dūs (the water or liquid of iron) probably means slag and not cast iron.

Discussion

The examination of the crucible steel remains and the review of the Islamic texts and ethnographic accounts, indicate that many different materials and methods were used to produce crucible steel. Apart from al-Beruni's brief comment that the blacksmith al-Dimasqi selected the clay and size of the crucibles, made the furnace, and utilised bellows, no other information about crucibles, furnaces or bellows is mentioned in these Islamic texts. The textual evidence of the crucible charge is not directly comparable with the proposed reconstruction from the archaeological evidence at Merv until further investigation into the amount of carbon in the given weight of the said carbonaceous material is determined. However, the texts can suggest what elements of the charge, such as the manganese, were deliberately added.

The texts indicate that narmahan and shaburqan were possible crucible charge ingredients used to supply the iron for transformation into steel. The form of the iron varied from filings to old nails, suggesting the use of recycling old iron or pieces too small to have any other functional use. It may be significant that the recipe that uses iron filing also requires coral and borax. The texts also indicate that many different types of carbonaceous matter were used including pomegranate rinds, oyster shells, orange peals, and gallnuts. This particular variety of materials again suggests recycling, since these materials are primarily waste products.

In light of the fact that magnesia was mentioned in six recipes as an intentional ingredient strongly suggests that magnesia was also added to some of the crucible charges at Merv. Although in modern language magnesia is MgO, magnesia has also been used to mean manganese (Merrian-Webster, 2000). In addition, the term "glassmakers magnesia" suggests MnO because glassmakers used MnO in glass production. Here it is argued that magnesia probably means MnO. The crucible slag at Merv formed two groups, one with a much higher percentage (12%) of MnO than the second group (2%) suggesting either a deliberate addition into the crucible or different sources, but considering the archaeological evidence along with the texts, the former seems to be the most likely cause. Manganese may have been added because it can counteract the effects of sulphur in the steel and promote the appearance of a Damascus pattern (see Chapter 4).

Other mentioned deliberate additions to the charge include salt, pyrite, nitrate, borax, and antimony. How much of these additions contributed to the composition of the iron or the slag would depend on a variety of factors including how much of the substance was added and the redox atmosphere inside the crucible. The salt would have vaporized as the crucible heated up and may have acted as a flux producing a glaze on the interior side of the crucible wall but it would not have effected the steel itself. The addition of pyrite is odd because the sulphur would have been detrimental to the steel, causing it to be "hot short" (brittle), however, the addition of manganese would have counteracted the detrimental effect. Dinnetz (2001) points out that nitrate is intentionally added to the charge which could have had a hardening effect on the steel product. The addition of borax and antimony may have had a similar effect.

Egg shaped crucible steel ingots are mentioned in the texts as well as appearing in the archaeological record as the final product. There is, however, a difference in the weight of the ingots determined from archaeological evidence (2 – 4.5 kg) and recorded in the texts (less than to 2 kg). The Islamic texts also make a direct connection between the ingots made of pulad and swords with a pattern. The texts state that pulad is associated with firind (farand, ferind) and firind is translated either as Damascus (Allan, 1979, 77) or pattern (Al-Hassan and Hill, 1986, 254). In particular, al-Beruni stated that Indian and non-Indian swords are made of pulad and that the steel is etched to bring out the pattern. Thus, the archaeological and textual evidence prove that crucible steel was produced in Central Asia using a variety of materials and the product was an egg shaped ingot that could be used to make a blade, which sometimes exhibited a Damascus pattern.

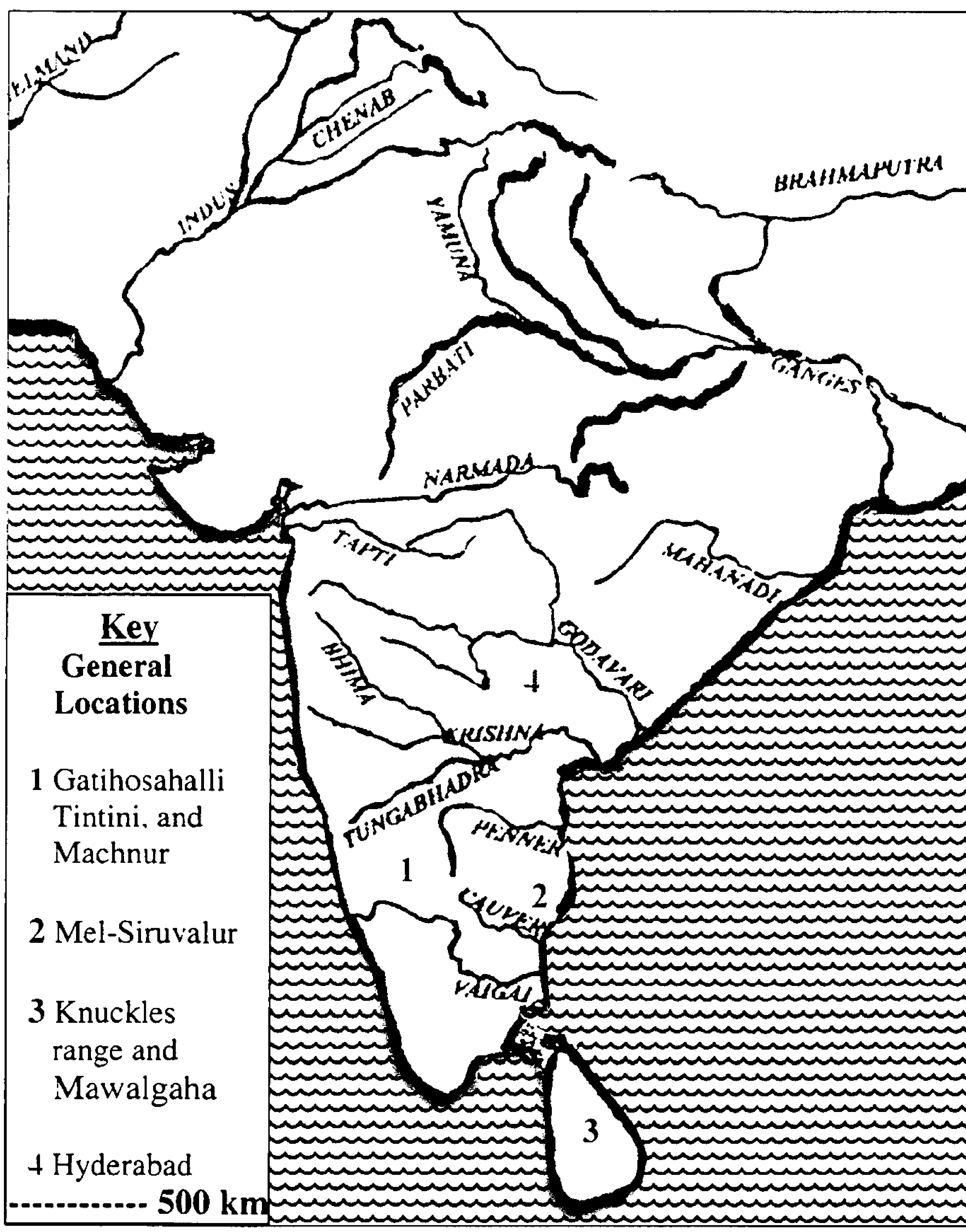
Indian/Sri Lankan Crucible Steel Terms and Production

There are many words in the different Indian languages for the word iron including lauha and loha. According to the Cologne Digital Sanskrit Lexicon (2001) there are also scores of words for steel including the following transliterated as piNDA7yasa, abhraka-sattva, cIna-ja, and tIkSNa4-loha. A variation of pulad also appears in Sanskrit as pollalwadeln, and pollalwad (Cologne Digital Sanskrit Lexicon, 2001). In addition, words translated to mean Damascus steel include baTTa-lohaka, zaikyAyasa, and loha4-ja (Cologne Digital Sanskrit Lexicon, 2001). However, it is not readily clear if these words really do refer to crucible Damascus steel or another variety of Damascus steel (see Chapter 3).

Terms interpreted by scholars such as Bronson (1986) and Craddock (1998) to be referring to Indian steel are al-Hind, hinduwani and hunduwany. Al-Hind or al-Hindi is the Arabic term used to denote steel from India. Juleff (1998, 10) points out that wani and waney are the Sinhalese terms for steel and to her knowledge, the words do not appear in any Indian language and do not appear to derive from Sanskrit. The use of the terms hinduwani and huduwany, in the literature might better be understood as steel from Sri Lanka, rather than implying all of India.

Indian/Sri Lankan crucible steel is commonly referred to as wootz. It is generally agreed that wootz is an English corruption of the word ukko or hookoo. Ukko is found in Canarese (Chakrabarti, 1992, 1). Hookoo is found in the Telegu language of Hyderabad, Tamin Nadu and Mysore areas (Prakash, 1989, 96). Telegu, Kannada, Tamil and Malayalam are Dravidian languages (non Indo-European) used in the southern Indian states of Andhra Pradesh, Tamil Nadu, Kerala, and Karnataka (Lowe in Allan and Gilmour, 2000, 69). The term wootz first appears in print in 1795 in Pearson's Lecture to the Royal Academy on Indian steel (Hadfield, 1931). This was during a time when Indian crucible steel was being sent to England for laboratory analyses with the purpose of understanding what made it apparently tougher than steel made in Europe. A discussion of the early interest in wootz, those who studied it, and its etymology can be found in Hadfield (1931).

Despite the extensive number of reports that claim the importance of India in producing vast quantities of wootz, few archaeological sites have been investigated. There are many ethnographic accounts of Indian crucible steel production (see Bronson, 1986), however, scientific investigations of crucible steel remains have only been published from four regions: three in India and one in Sri Lanka (e.g. Rajan, 1989-90 and 1990; Craddock, 1998; Srinivasan and Griffiths, 1997; Anantharamu *et al.*, 1999, Freestone and Tite, 1986, Rao *et al.*, 1970; Wayman and Juleff, 1999; Lowe, 1989, 1991) (Map 8).



Map 8: Crucible Steel Production Sites in India and Sri Lanka.

Bronson (1986, 39-46) concluded that there were four different varieties of crucible steel:

1) South Indian Processes;
2) Hyderabad Process;
3) "Schwarz" Process;
4) Pseudo-Wootz process.

Bronson states that the "Schwarz" process and the Pseudo-Wootz process are not true traditional wootz processes and there are no archaeological studies of remains from these processes; therefore, they are not further discussed here.

The characteristics of the South Indian process were established by combining the information from ethnographic accounts reported by Bronson (1986) and descriptions found in archaeological reports. Based on the contents of the ethnographic reports Bronson (1986) determined that the South Indian processes had certain "common denominators":

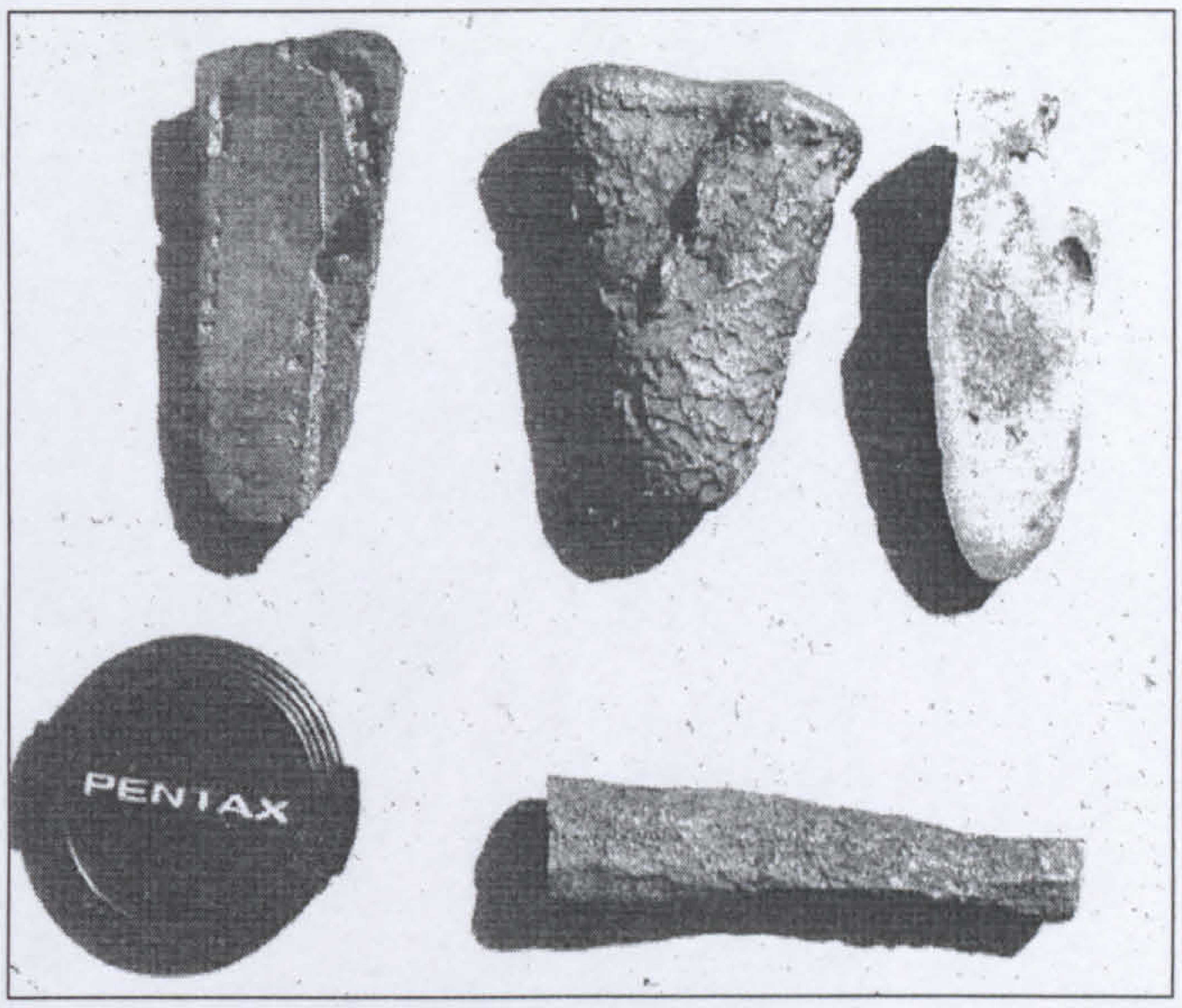
1) They used "a sealed crucible charged with iron and vegetable matter";
2) It is a haphazard procedure resulting in many failed crucible steel ingots;
3) It is "never said by first hand sources to yield a metal with a Damascene structure"; and
4) There is weak division of labour (Bronson, 1986, 39-40).

Fifteen additional "common denominators" (characteristics) were determined by reviewing the information contained in archaeological and ethnographic reports. The reports did not record all the same types of information (Table 27 and 28).

In India, the site at Kodumanal is attributed to the 3rd century BC - 3rd century AD and is the earliest securely dated site containing crucibles which may have been used for crucible steel production (Rajan, 1989-90 and 1990; Craddock, 1998, 49; Srinivasan and Griffiths, 1997). The reports state that iron slag and a large furnace stacked with vitrified crucibles was uncovered. Srinivasan and Griffiths (1997) examined a couple of fragments from Kodumanal (stressing that it is a preliminary investigation). Their analysis of the crucibles clay matrix testified that it was iron rich containing around 50% FeO. Srinivasan and Griffiths (1997, 117) report that the crucibles resemble the crucibles from Mel-Siruvalur (see below) however no iron or steel prills, nor lids have been found so far, thus, the crucibles are not confirmed as remains from crucible steel production. Therefore, the site cannot yet be identified as the earliest crucible steel production centre until more analyses are performed or more evidence is reported, such as the presence of iron/steel prills.

Remains from Mel-Siruvalur, Tintini, and Machnur were positively identified as being from crucible steel production but unfortunately the remains are only surface finds and the date of production is unknown. Srinivasan and Griffiths (1997) report that the crucibles from Tintini and Machnur resemble those from Mel-Siruvalur. The crucibles are aubergine shaped, have a greenish black glassy slag that appeared to have floated over a convex meniscus, a wad of clay for a lid, a slag fin in the middle of the crucible with a honeycomb pattern beneath the fin. White quartz was found in the exterior black glaze and apparently it was applied to the exterior surface to prevent the attack of fuel ash. Remnants of organic material can be observed as impressions in the lids. Rusty splashes were also observed on the interior walls and the bottom of the lids and a prill is reported to have a structure that indicates it was slowly cooled but no details on its structure are given. At Mel-Siruvalur the crucibles may have stood in a sand bed during firing (Srinivasan and Griffiths, 1997, 116).

Contemporary ethnographic descriptions from the site of Gatihosahalli formerly called Mysore, now in the region called Karnataka, were reported by Iyer (Anantharamu *et al.*, 1999, 13-14). Numerous scholars have studied the crucible steel remains (Anantharamu *et al.*, 1999, Freestone and Tite, 1986, Rao *et al.*, 1970, Srinivasan and Griffiths, 1997). The crucibles are conical in shape and composed of ferruginous clay with rice husk and straw temper (Figure 88). Glassy green slag is present inside the crucible. Pieces of unconsolidated iron blooms were also found and are assumed to be part of the crucible charge. Presumably these blooms were then forged to a billet to fit into the crucible (Figure 89). Based on ethnographic accounts and impressions of organic material on the interior surface of the lid, apparently carbonaceous material was placed into the crucible. The crucibles were stacked in the furnace and fired (Srinivasan and Griffiths, 1997, 121). The carbonaceous material carburized the wrought iron billet and the result was a porous high carbon steel ingot with less slag than the original bloom. Examination of a failed ingot revealed a wrought iron core with a higher carbon surface, which becomes progressively higher in carbon away from the centre (Anantharamu *et al.*, 1999, 20).



Figures 88 and 89: Crucible from Gatihosahalli (left) and billets for the crucible charge and a steel ingot from Gatihosahalli (right)
(Taken from Craddock, 1998, 57).

The earliest confirmed crucible steel site is located in the Knuckles range in the northern area of the Central Highlands of Sri Lanka. Radiocarbon dating of associated charcoal dates the site to the 6^{th} - 10^{th} centuries AD (Wayman and Juleff, 1999, 29). Archaeometallurgical remains from the site include crucible fragments and plano-convex slag cakes, however, Wayman and Juleff (1999, 29) do not provide details of the size of these slag cakes or if they seem to be related to smelting, smithing or the crucible process. The crucibles are reported as pear or light bulb shaped with thin walls and the same fabric as the crucibles from Mawalgaha (Wayman and Juleff, 1999, 29).

Mawalgaha is where Coomaraswamy documented crucible steel production in 1904 (Wayman and Juleff, 1999, 26). One of the most distinguishing features of the Mawalgaha crucibles is that the crucible has two slag fins. The first runs around the internal circumference about 1/3 of the way along the height of the crucible; the second is at right angles to this fin, running along the length of the crucible. This indicates that while the metal was molten the crucible was placed on its side and this is corroborated by Coomaraswamy's ethnographic report (Juleff, 1998, 91). The result was an elongated steel ingot. The examination of two crucible steel ingots revealed that they were composed of steel with both eutectic and hypoeutectic regions that cooled moderately slowly after solidification (Wayman and Juleff, 1999, 30-31). They are porous with shrinkage cavities and sulphur and phosphorous non-metallic inclusions (Figure 90).

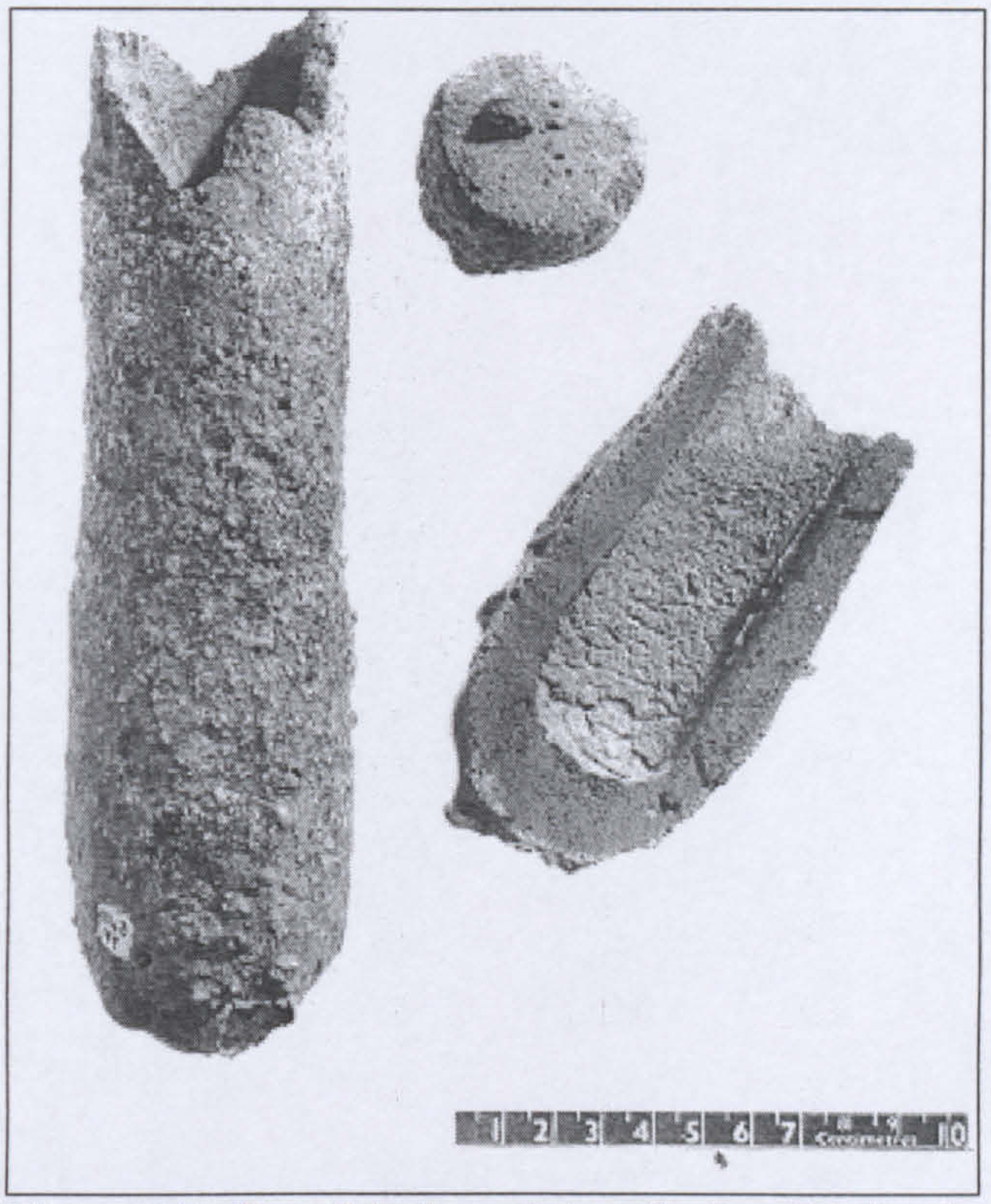


Figure 90: Crucible from Mawalgaha, Sri Lanka
(From Wayman and Juleff, 1999, 28).

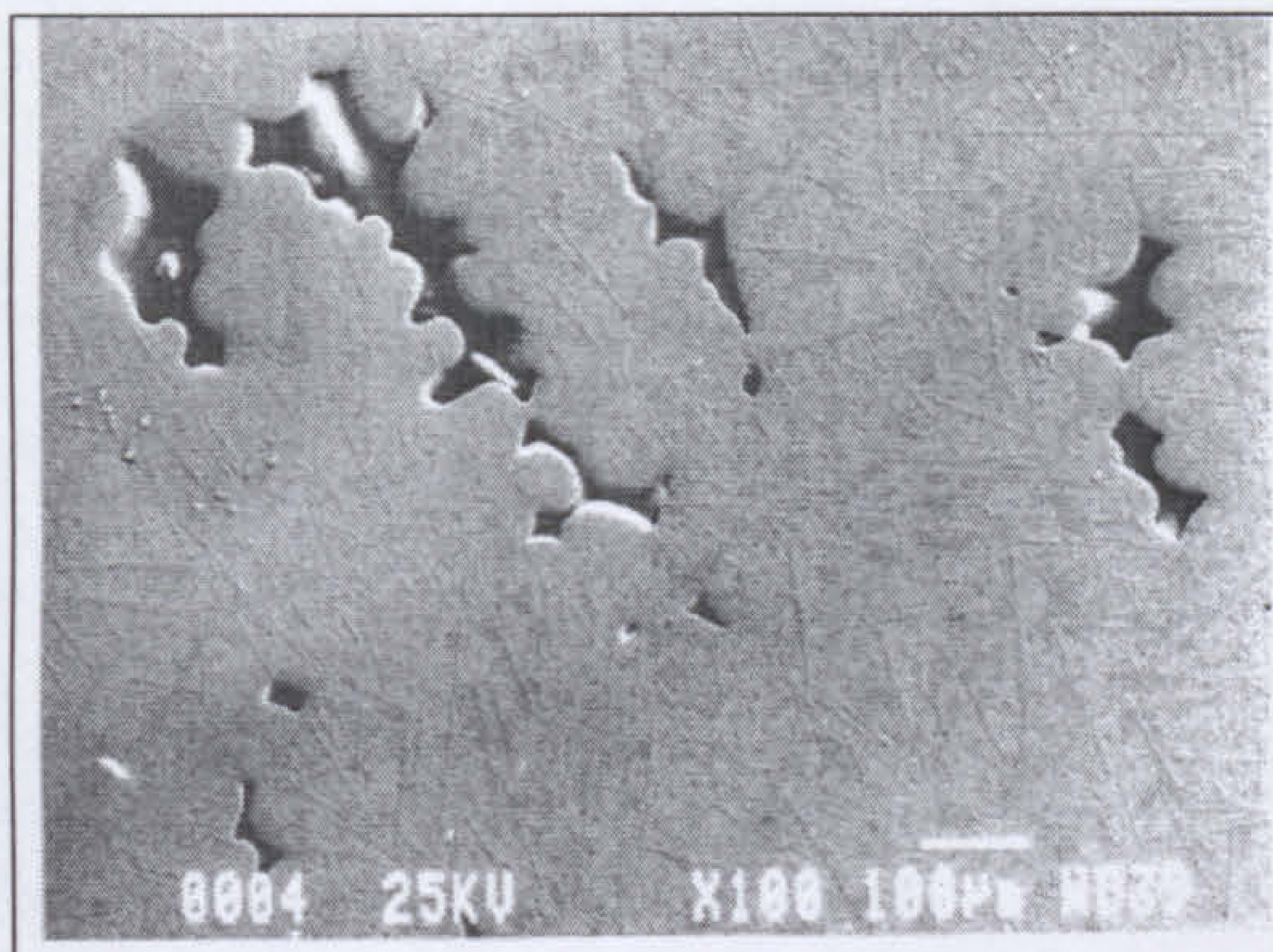


Figure 5: Ingot B showing interdendritic shrinkage porosity. Nital etch. Scanning electron micrograph. Magnification 75x.

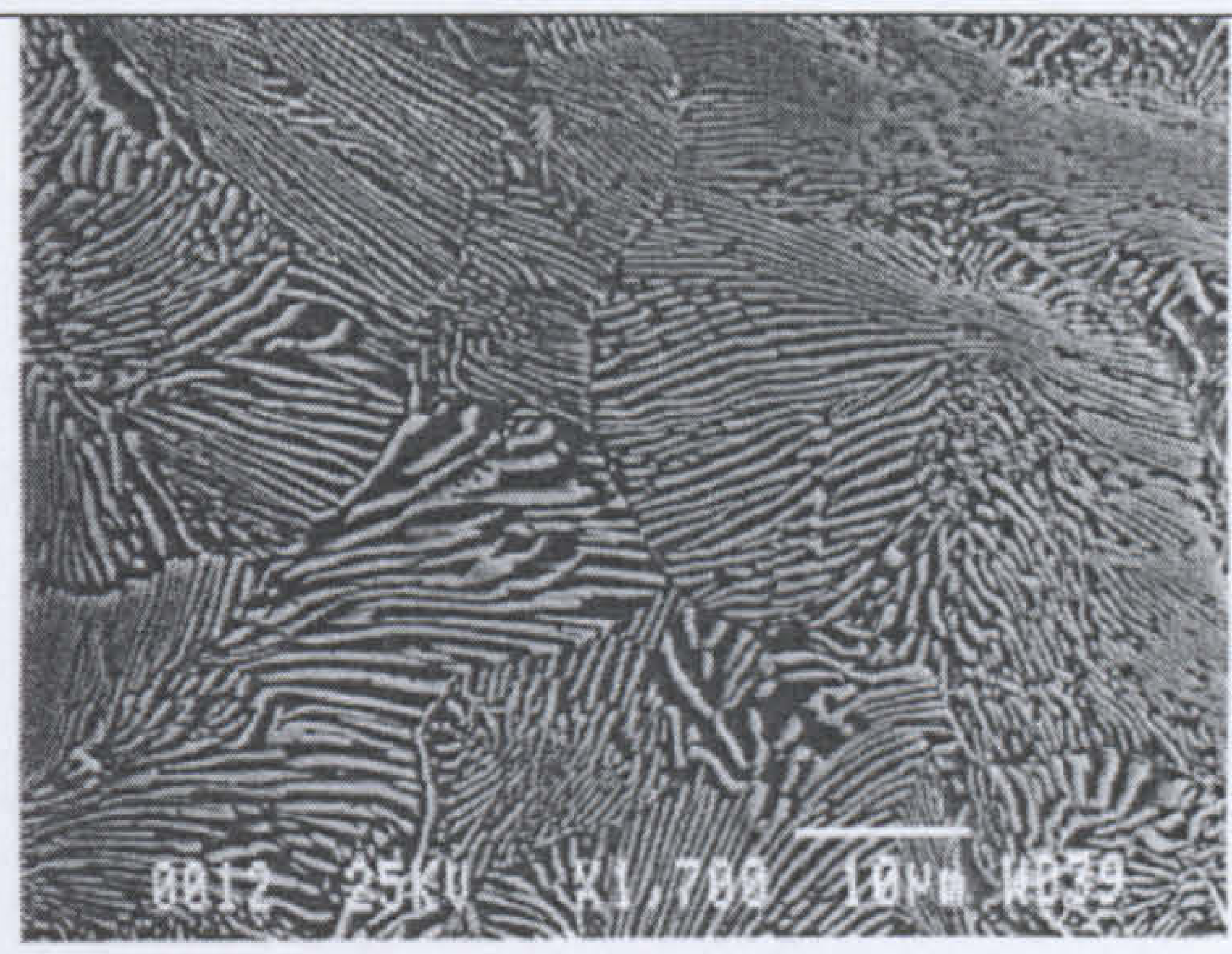


Figure 7: Ingot A showing pearlitic microstructure. SEM micrograph. Nital etch. Magnification 1250x.

Figure 6: Ingot A showing dendritic solidification pattern. Stead's reagent. Optical micrograph. Magnification 5.5x.

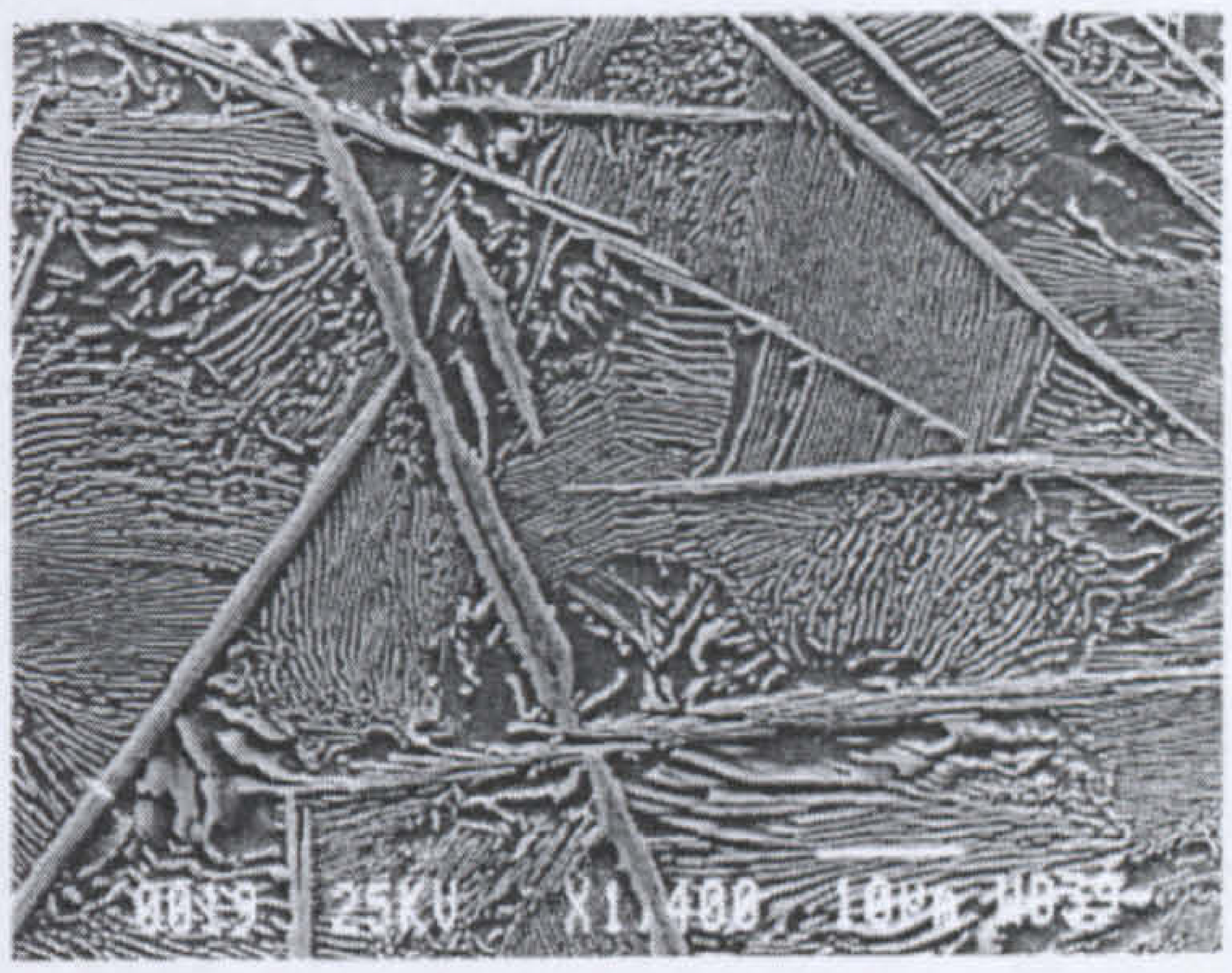


Figure 8: Ingot A hypereutectoid region, Widmanstatten cementite in pearlite. SEM micrograph. Nital etch. Magnification 1050x.

Figure 91: Photomicrographs of the metallography of crucible steel from Sri Lanka (from Wayman and Juleff, 1999, 31).

In conclusion, the following characteristics are typically found in the crucible steel process employed in South India/Sri Lanka, commonly referred to as wootz (Tables 27 and 28). In all the crucibles rice husks were used as temper. The shapes of the crucibles are conical or aubergine shaped (South Indian) or elongated, pear-shaped or light bulb shaped (Sri Lanka). The base of the crucible was either rounded or pointed. "Earth" or "clay" was put into the top of the crucible to seal it, but occasionally separate preformed lids were used. The crucible charge used was one type of iron and either wood and/or leaves. At most sites the steel solidified relatively quickly. The crucibles were stacked together in the furnace, often in a cone shape.

Table 28: Selected Characteristics of Indian/Sri Lankan Crucibles

Location / *Characteristics*		South India		Sri Lanka
		Gatihosahalli	**Mel-Siruvalur**	**Mawalgaha**
Fabric	**Clay**	Ordinary ferruginous	Ordinary ferruginous	Ordinary ferruginous
	Temper	Rice husks, straw	Rice husks	Rice husks
Form	**Shape**	Conical	Aubergine	Elongated tube
	Base	Pointed	Curved	Rounded
	Lid	Wad of clay	Wad of clay	Clay button with small holes
	Height	~ 16 cm	*NA*	~ 18.6 cm
	Diameter	3-6 cm at top	~ 7 cm at top	3.4 cm

Table 29: Selected Ingot, Slag and Furnace Features

Location / *Characteristics*		South India		Sri Lanka
		Gatihosahalli	**Mel-Siruvalur**	**Mawalgaha**
Ingot	**Shape**	Cone shaped	Puck?	Elongated
	Size		~ 2.5-3 cm	
Composition	**C%**	0.7%- 0.8% C	1-1.5% C	Eutectic Hypereutectic
	Cooling Rate	Taken out and quenched	Possibly slow cooled	Removed when liquid
Slag	**Appearance**	Glassy green slag	Greenish black and glassy	2 slag fins
Furnace	**Floor**	Earth?	Sand	Earth?
	Position of crucibles	Conical heap	Stacked	Semi-circular
	Number of crucibles	50-55	*NA*	6

Hyderabad Process

Remains from crucible steel production at Hyderabad, central Indian at Konasamudram, Nizamabad district, formerly called Golconda, Andhra Pradesh, have been studied by Lowe (e.g. 1989a, 1991) and reported by Voysey (1832). Bronson (1986) primarily uses Voysey's account (1832, 245-247) as his source of information on the Hyderabad process. Bronson's argument for differentiating the Hyderabad process from the South Indian Process is the crucible charge. The South Indian process used iron and carbonaceous material whereas the Hyderabad process apparently used two types of iron. Research by Lowe (1989a, 1989b, 1991) has provided additional information confirming that the characteristics of the Hyderabad process are distinct from those of the South Indian wootz process. When compared to the crucible steel remains from Central Asia, the Hyderabad remains have more characteristics in common with those remains than with the South Indian/Sri Lankan remains.

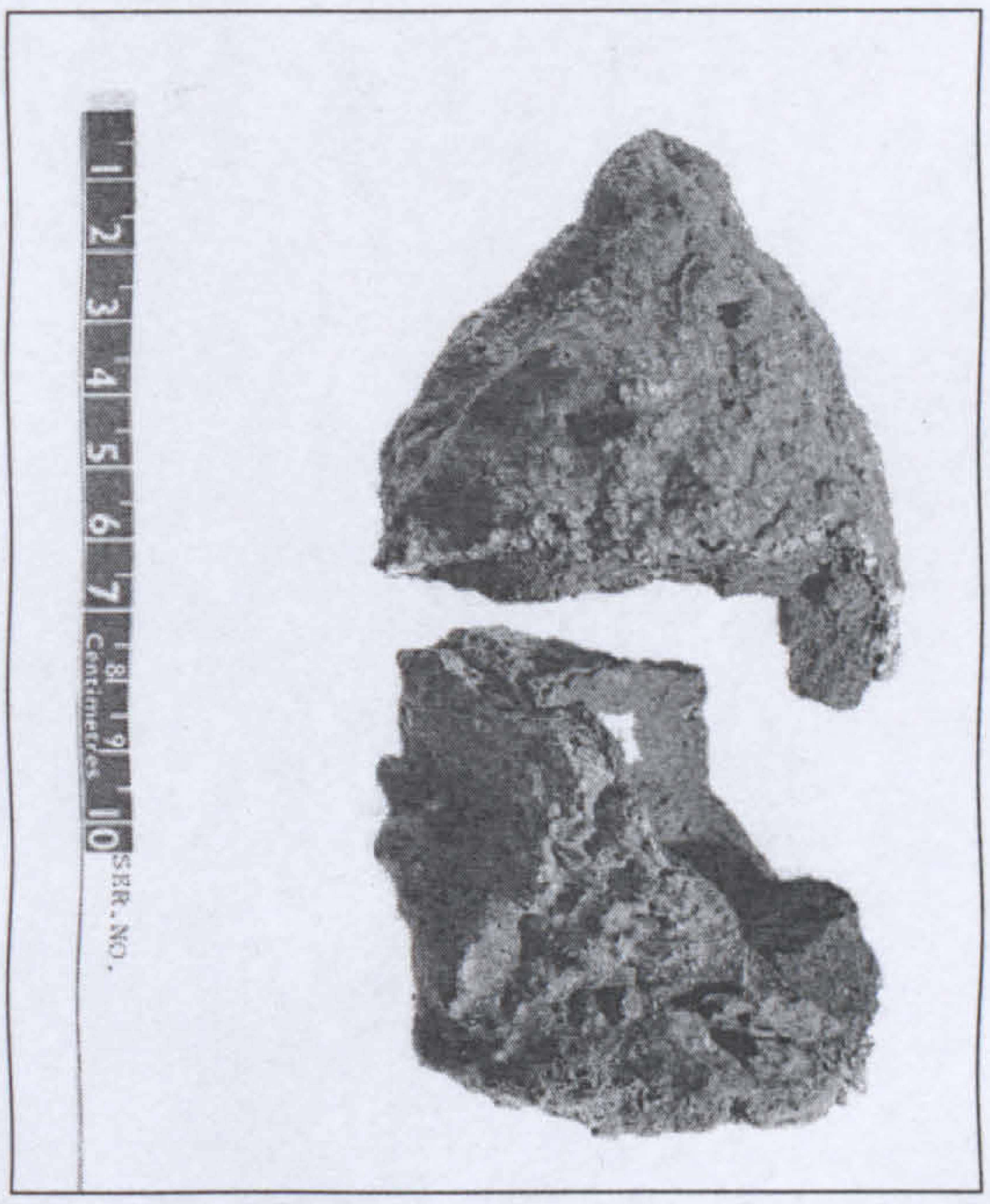


Figure 92: Crucible from Konasamudram (Hyderabad)
(Taken from Craddock, 1998, 54).

The shapes of the Hyderabad crucibles are similar to those from Central Asia; both are cylindrical and flat bottomed, except that the Hyderabad crucibles are shorter (Figure 92). However, the interior diameter of the Hyderabad crucibles ranges from 2.5-12 cm (Lowe, 1989b, 732). The lids of the Hyderabad crucibles are made out of a lump of clay but some crucibles have a "triple crucible" cover, consisting of three small crucibles luted together (Lowe, 1989b, 733-734). The interior surface of the Hyderabad lids is covered with small iron prills (Lowe, 1989b, 734) similar to those observed in the interior walls and interior surface of the lids on the crucibles from Merv. Central Asian and Hyderabad crucibles have gravel or similar debris embedded into the bottom surfaces (Chapter 1 and Lowe, 1989, 247). The flat bottoms and debris indicate that both the Central Asia and Hyderabad crucibles sat on the floor of the furnace, whereas the South Indian crucibles were stacked. The temper used in the Hyderabad crucible lids is different from the body. The lids have grog, quartz and feldspar as temper (Lowe, 1989, 246). The temper of the crucibles from Hyderabad is similar to other Indian crucibles in that they both use rice husks. Lowe (1991, 10) reports that composition of the ceramic matrix is around 70% SiO_2 and 30% Al_2O_3 thus indicating that the clay is more similar to the Central Asian crucibles, which also are relatively refractory and contain fewer impurities than the South Indian crucibles which are made of ordinary ferruginous clay. It is the carbon from the rice husks and the reducing atmosphere inside the furnace which gives the Hyderabad crucibles their black colour, making them superficially appear more similar to the South Indian crucibles than they truly are.

Voysey (1837, 247) reported that the crucible charge contained "kanch" and two different types of iron. The first is described as a "porous reddish grey bloom", while the second was "moderately compact and of a brilliant white fracture". These have been understood by Allan and Gilmour (2000, 72-74) to be "small pieces of fused glassy furnace waste together with two pieces of white cast iron and three pieces of bloomery iron". Voysey (1832) also reported that the crucibles were heated for 24 hours, then slowly cooled in the furnace and repeatedly annealed three to four times until soft. Lowe (1989b, 732), however, states that the crucibles were removed from the furnace while molten. The resulting ingot is reported by Lowe (1989b, 732 -733) to be a white cast iron ingot, which exhibits a dendritic structure of cementite, lamellar pearlite, interstitial steadite, and shrinkage porosity.

A summary of selected characteristics of the Hyderabad process is presented in Table 29.

Table 30: Selected Characteristics of Hyderabad Process

Clay Fabric	Refractory
Temper	Lid contains crucible grog, quartz, feldspars
	Body contains rice husks
Crucible shape	Cylindrical with a conical lid
Crucible size	Varies from 2.5 – 12 cm interior diameter
Internal diameter	~ 12 cm
Base	Flat
Charge	Cast iron, wrought iron and slag
Slag	Fin
Ingot size	Presumably same as internal diameter
Ingot composition	White cast iron
Ingot shape	Cake
Ingot weight	110 g and 50 g (Lowe, 1989b, 731) 680 g and 1260 g (Voysey, 1932, 246)
Cooling rate	Slowly or quickly
Exterior glaze	Colour and thickness variable, thicker at the bottom
Firing time	24 hours + annealing
In Furnace	Placed on floor (gravel on bottom of crucible)

Chinese Crucible Steel Terms and Processes

In China, a material known as pin-tieh was said to have derived from western lands. According to Laufer (1917, 515), pin-tieh was a product of Sasanian Persia, India and Hami. Archaeological evidence of crucible steel objects from this period support the Chinese texts (see Chapter 4). Pin-tieh was described as "Persian" in the sixth century and as "Kashmirian" in the tenth, and thought to be so "...hard and sharp that it can cut metal and hard stones" (Schafer, 1963, 263). In the Ko Ku Yao Lun, dating from 1388 AD, pin tieh "is produced in the Western Barbarian Regions and has patterns of spirals, sesame seeds or snow flakes. These patterns on the blade of the sword or knife can be brought out by cleaning and polishing it with a piece of gold-thread alum. Steel [of this variety] is more expensive than silver...I have seen a pair of scissors made of this kind of steel with chased and gilt patterns in the outside and silver inlaid Mohammedian characters on the inside. It was beautifully made" (David, 1971). The high quality of the steel, the associated Islamic writing and pattern all point towards Pin tieh being crucible steel. In addition, knives, swords and scissors were made of crucible steel (see Chapter 4). Schafer supposed that the name pin-tieh derived "probably from an Iranian tongue by way of an Indian Prakrit form such as Pina" (Schafer, 1985, 263), whereas Needham (1980, 539) supposes that the word is from a Turkic or Iranian language.

Methods of producing iron or steel in a crucible are also known from China, however the processes are different from those used in Central Asia, India or Sri Lanka and they are not associated with a pattern. Ore and coal were packed in a crucible and heated and the result was iron, steel or cast iron (Wagner, 1993, 289). In Shanxi, Northern China, crucibles had been used to smelt iron since at least the tenth century (Hara, 1992, 131) until the 19th century and the technology spread throughout China to Manchuria (Hara, 1992, 131).

Comparative Analysis

Undoubtedly the use of crucibles in iron and steel processing was used in many locations in Asia for at least a thousand years. The Chinese method does not seem to be directly related to the Central Asian, Indian or Sri Lankan processes because it is a primary smelting process rather than a secondary refining and carburising process.

There are more differences than similarities between the processes used in Central Asia and South India/Sri Lanka. The primary similarity is that they all produced an iron-carbon alloy ingot in a crucible. To the modern metallurgist, the details of the process as practiced in antiquity might not be as significant as the quality, composition and behaviour of the ingot and final product after forging, but to those who are interested in the history of technology and related disciplines, the differences are as important as the similarities. The materials and techniques used in Central Asia and India/Sri Lanka processes would have affected the quality, composition and behaviour of the crucibles and ingot. In addition, how wasteful or efficient the processes were, can be assessed.

The majority of scholarly literature refers to all crucible steel made by traditional methods as wootz (e.g. Bronson, 1986; Figiel, 1991; Verhoeven, 2001). When they do acknowledge that it was produced in Central Asia, it is implied that it is a variation of the wootz process (e.g. Bronson, 1986, 42-45). Previously no attempts have been made by scholars to differentiate between the crucible steel processes used in India/Sri Lanka and Central Asia.

Crucible fragments are by far the most abundant find from all the crucible steel production sites. It is apparent that the environment around the crucible steel production centres influenced the construction of the crucibles, particularly in Central Asia. Lowe (1989, 247) states that the Hyderabad crucibles are not related to any Indian pottery making traditions. However, the use of ordinary clay with rice husks as temper has been mentioned in Sanskrit texts dating back to at least the seventh – thirteenth centuries (Lowe, 1989, 249). This differs from the Central Asian crucibles. In Uzbekistan the method of shaping the ceramic around a pre-made form can be traced back to the Bronze Age Chust culture (Zadneprovskii, 1962, 321-323 in Rehren and Papakhristu, 2000). In the Merv Oasis, the use of a wheel to form pottery dates back to the second millennium BC (Hiebert, 1994, 171) and quartz temper was used in cooking pots at least from the Sasanian period if not earlier. Grog and organic temper was also used in some Sasanian wares (Herrmann *et al.*, 1994, 42).

The highly refractory clay used at Merv, however, was imported. This indicates a reliance on trade without which the process could not be performed. Indeed the large scale production at Akhsiket points towards trade of ingots and/or finished products from the city and trade of materials from neighbouring areas. It has not been determined where the raw materials used at Akhsiket derived from, but the Ferghana valley is surrounded by mountain ranges rich in raw materials. In India the materials appear to be local, including local smelting of iron, and therefore the process does not rely on fairly long distance trade. Trade seems to be an important part of the process in Central Asia whereas it is not a necessary part of Indian production, as it can be produced within the society without a heavy reliance on trade, except for the early modern trade in crucible steel ingots.

In Central Asia and Hyderabad, the crucibles sit on the floor of the furnace and gravel-like material is placed in between the crucibles, indicating that the crucibles were not closely adjacent to each other, thus allowing hot air to flow between the crucibles. In contrast, all known crucibles from South India/Sri Lanka do not have flat bottoms and were in close contact with each other. This would have impeded the dispersal of heat around the crucible and probably accounts for the comparatively high number of failed products.

The cooling rate of the crucible steel ingots also seems to differ, although further research is needed to determine how significant this difference is in relation to the final product. The evidence so far indicates that in Central Asia the crucible, with the ingots inside, cooled slowly inside the furnace (see Chapter 1). Conversely, those from South India/Sri Lanka are usually recorded as being removed from the furnace while still hot. This would affect the solidification rate of the metal and would influence the final microstructure and ease of forging (see Chapter 3 and 4).

During the solidification of the liquid metal, the ingot shape is a virtual cast of the crucible's interior. All known crucible steel ingots from Central Asia are egg shaped. These egg shaped ingots were also noted by al-Beruni during the 10^{th} century (Said, 1989). The shapes of the ingots from south India/Sri Lanka, however, tend to be more varied but never egg-shaped.

It must therefore be concluded that the materials and techniques associated with the crucible steel process in Central Asia (pulad) and those used in India and Sri Lanka (wootz) are significantly different.

Chapter 3:Damascus Steel

"All that has been written about this product does not provide me with adequate information"
Anosov (Bogachev, 1986, 42)

The history of crucible steel is intrinsically linked to Damascus steel. The term Damascus steel appears in discussions in Islamic texts, historical ethnographic reports and modern laboratory analyses. Despite all this research, many inaccuracies, fallacies, and misunderstandings still appear in scholarly and popular literature, primarily due to the use of secondary sources and the repeating of myths as facts, including that Damascus steel was forged in Damascus from imported Indian wootz ingots, and that the technique to make Damascus steel was "lost". Historical analysis and modern replication experiments on Damascus steel have shed light on many factors of the crucible steel processes and the factors necessary to produce the Damascus pattern. Many of these factors could not be deduced from archaeological evidence or texts. The information gathered from Damascus steel replication experiments can be used to identify the variety of materials and methods that could be used to produce crucible steel. However, many questions including the relationship between the ingot's composition, cooling rate and pattern, still remain. It is remarkable that Anosov's statement (see above) still holds true over 150 years on.

Origin and Meaning of the Phrase Damascus Steel

There are four varieties of swords or steel to which the adjective Damask, Damascene, or Damascus is applied: pattern-welded, inlayed, preferentially etched, and crucible. The pattern-welded variety is often called mechanical Damascus because it is made by forge-welding several pieces of iron or steel together to form a decorative (and often functional) pattern such as Merovingian blades (Tylecote and Gilmour, 1986, 252). For centuries this method was commonly used throughout Europe (Sachse, 1994). The process was employed to produce the patterned Japanese Samurai swords and the Kris swords of Southeast Asia (Sachse, 1994). Patterns and decorations made by inlaying different types of metals or jewels onto the blade's surface appear on swords from Russia. The method has a long history at least from the 14th century. Ibn-al Uhkuwwa (d. 1329) mentions inlay as one method used for producing imitation crucible Damascus steel (Al-Hassan, 1978, 39), thus "forging" (so to say) the crucible Damascus pattern. Preferentially etching a pattern on the blade was used in nineteenth century India, perhaps to imitate the crucible Damascus steel pattern. The inlay and etching methods are often called artificial Damascus (Figiel, 1991, 27). The fourth variety is made from crucible steel, sometimes called oriental Damascus, true or crystalline Damascus (Bronson, 1986, 13).

The use of the adjectives crucible, pattern-welded, inlayed or etched together with Damascus, Damask or Damascene should be used in future publications to avoid confusion. Using these adjectives, the method used to form the pattern (if known) is clear and free from ambiguity. Unless otherwise noted, the term Damascus steel is used here only to denote the crucible variety.

The lack of proof of Damascus ever having actually been a centre of sword production has been argued by Elgood (1994, 103-108). However, large Islamic cities usually had industrial areas and Damascus was probably no different. The origin of the name Damascus steel is frequently attributed to the crusaders, who, as the legend goes, were introduced to these blades in Damascus and brought the word and the legend of the steel back with them upon their return to Europe (e.g. Sherby and Wadsworth, 1985, 112).

Although this assertion is common, no reference to crusaders having used the term has ever been reported in any of the literature. Allan and Gilmour state (2000, 77) that the French traveller Bertrandon de la Brocquiere in 1432 first acquainted Europeans with the term Damascus steel. Brocquiere reported, "Damascus blades are the handsomest and best of all Syria... I have nowhere seen swords cut so excellently. They are made at Damascus, and in the adjoining country..."(Ziadeh, 1964, 46-47). The use of various forms of the adjective "Damascus" is recorded in English from the late 16th century. According to the Oxford English Dictionary (CD), the term was used in 1562 to describe how a certain man was like a Scimitar. During the late 16th and 17th century there are a number of quotes associating Damascus swords with Turks. Joseph Moxon stated that Damascus steel rarely comes into England unwrought but Turkish Symeters (*sic.*) are made from it (Moxon, 1677, 56). The French gem trader, Chardin, during the 17th century, mentions Damascus steel. He describes steel, calls it pulad (poulad), and states that the phrase Damascus steel was used to distinguish these swords/steel from those of Europe (Bronson, 1986, 24).

There are more credible roots for the origin of sword names. The Islamic writers al-Kindi and al-Beruni name swords based on surface appearance, place of production or forging, or the name of the smith. Al-Kindi, for example, refers to al-bid (white swords), to Khurasaniya swords produced and forged in Khurasan, and swords called "Zaydiya (that) were forged by a man called Zayd, and hence they were attributed to his name" (al-Hassan, 1978, 35). In addition, al-Beruni describes swords named after locations of workshops and mines. It appears that during the early Islamic period people were uncertain of the origins of sword names, for al-Beruni states that swords with the provenance of Mashrafyiyah may refer to the name of the ironsmith Mashraf or the village called Mazarif (Said, 1989, 217). There are three likely sources for the term Damascus in the context of swords. The word for water in Arabic is, *damas* (Sachse, 1994, 13) and Damascus blades are often described as exhibiting a water-pattern on their surface. Al-Kindi called swords produced and forged in Damascus as Damascene (al-Hassan, 1978, 35). Additionally, al-Beruni mentions a sword-smith called Damasqui who made swords of crucible steel (Said, 1989, 219-220). Any or all of these may have inspired the term "Damascus steel" swords but it certainly were not crusaders who coined the term. The term "Damascus steel" is found in the writings of al-Jaubari (died 1232). He reported that ".... a prescription for a (good) cutting sword: Indian steel or Damascus steel is taken and a sword is made..." (Al-Hassan, 1978, 39). Ibn-al Uhkuwwa (d.1329) also used the phrase Damascus steel (see above). These references indicate that the adjective "Damascus" was being used to describe steel centuries before the term "Damascus steel" was reportedly used in Europe.

Historical Analysis and Replication Experiments

The reputation of Damascus swords, as strong, sharp and flexible, led to research into the mechanisms that caused its apparent superior properties. Crucible and Damascus steel have been studied in earnest since the late 18th century and continue to the present day. The pattern was associated with high quality steel. A review of the early experiments is used here to ascertain why, where and when certain claims about crucible steel and Damascus steel began, such as the introduction of the term wootz and its association with Damascus steel. Replication experiments also suggest materials and methods that could have been used in antiquity to produce crucible steel in addition to necessary aspects of the process which cannot be deduced from archaeological evidence alone.

"Some may have been good enough scientists not to allow the possibility of getting rich lead them into actual falsification of evidence, but a degree of suppression and obfuscation can be expected in the writings of all specialists of the period who worked on the problems of wootz and Damascus steel" (Bronson, 1986, 30). However, no real secrets, suppression or obfuscation exists in the primary literature. It is in the secondary literature and "popular" papers written on Damascus steel where "ghost" citations (information stated as facts but without an original reference, see Wagner, 1993, 307), become the norm. During the 1800s, Abbott saw firsthand Damascus steel being produced by traditional methods in India and by "modern" replication methods performed by Anosov in Russia (see below) and he stated "It is a reflection upon the arts of England, that it is not known there, as there is no difficulty whatever in producing it" (Abbott, 1856, 358).

Summary of English and French Research

The earliest recorded inquiry in England into Damascus steel was by Moxon (1677) who reported that Damascus steel was the best type of steel but it was the most difficult to forge and it would red sear (be "hot short", see below). He also stated that the workmen believed it was cast steel and was enormously valuable for making punches etc. Moxon was also interested in where the steel was originally made and stated that a Mr. Boyl "hath been very careful and industrious in that inquiry; giving it in particular charge to some Travellers to *Damascus* to bring home an account of it: But when they came thither they heard of none made there, but were sent about fifty miles further into the Country and they were told of about fifty miles further than that: so that no certain account could be gained where it is made" (Moxon, 1677, 56). The next reported investigations during the 18th century were in France by Réamuer (Belaiew, 1918, 419) who noted that ingots from the Levant were difficult to forge but easier to forge than those from Egypt (see below).

Interest increased in England during the late 1700s when Dr. Helenus Scott of Bombay gave so-called "cakes" of crucible steel to Sir Joseph Banks, the then President of the Royal Society. Banks sent the specimens to England for examination and put in a request for more information about the production of crucible steel in India. Banks gave the "cakes" to Pearson, Stodart, and Mushet to study. This set the stage for many assertions that still exist in English language literature today, specifically that India was the *primary* supplier of wootz crucible steel throughout history and that Indian wootz steel was the material used to produce Damascus swords.

George Pearson studied the "cakes" and in 1795 gave a lecture to the Royal Society where he was the first Britain to state that it was a type of steel, and also to use the term wootz in print. He makes no association between wootz and any pattern.

In 1804 the metallurgist David Mushet received 5 "cakes" from Banks but these do not appear to be the same "cakes" which Banks originally sent to Britain, as Mushet mentions Pearson's earlier experiments. Mushet discusses numerous papers on the manufacture of wootz in India and included a letter from Heath (1839, 390-397). Mushet describes the "cakes" external surface appearance in great detail, he remarks on how well they forged, in addition he provides information of his own experiments. Mushet does use the term wootz in the text but does not mention any pattern or the term Damascus steel, except when he makes a tangential comment that the Damascus pattern is a mixture of soft iron and steel (Mushet, 1840, 663). This comment of mixing soft iron and steel, however, suggests that Mushet was referring to the pattern-welded variety not crucible Damascus steel.

Crucible steel research had an impact on the development of modern cast steel and alloy steel. Although Huntsman in the mid 18th century is stated to be the first modern researcher to produce steel in a crucible, it is Mushet who patented a "*Wootz*" type process in 1800 (Rostoker and Bronson, 1990, 132). Banks also gave samples to the cutler James Stodart (1760 - 1823). In 1818 Stodart approached Michael Faraday (1791-1867), with one of Banks "cakes" to "ascertain whether any other elements were present in the wootz than iron and carbon" (Faraday, 1819, 288). Faraday also analysed a piece of English steel to compare the compositions. He then set out to replicate wootz in the laboratory of the Royal Institution but was unsuccessful. In his paper he does not mention any pattern. The purpose of the research was not to replicate the pattern, but improve the quality of the steel, initiating research into alloy steels that are still widely used today. Faraday began to alloy steel with platinum, rhodium, silver, nickel, and tin, the same elements as he alloyed with copper.

The first reference to an apparent relationship between wootz and the Damascus pattern appears in Stodart and Faraday's 1820 paper on alloys. "We have ascertained by direct experiment, that wootz, although repeatedly fused, retains the peculiar property of presenting a damask surface, when forged, polished and acted upon by dilute acid" (Williams, 1965, 113). Apparently this notion that wootz produced a Damascus pattern was already accepted in the scientific community as Bréant also discusses wootz and the pattern in a paper published in 1824. It is important to realize that Faraday's connection between wootz and a Damascus pattern was based on his alloying replication experiments, not the examination of imported wootz. His assumption, therefore, of wootz producing a Damascus pattern has led to much confusion in the subsequent literature.

Faraday's initial analyses on the imported wootz cake influenced Jean Robert Bréant (Inspector of Assays at the Paris Mint) in France. It was after Bréant tried to alloy silicon and aluminium with steel that Faraday realised that the Damascus pattern was the result of excess carbon in the steel and the slow cooling which allows separation and that if it is cooled suddenly it will not appear (1824, 267-271) (see below). In 1821 Bréant published a paper stating that Faraday and Stodart were mislead by thinking that it was the alloying elements which affect the quality of the steel. Bréant describes the effect of many of the alloying elements on steel and how to successfully forge it. It is important to note that Bréant describes the crucible steel replication process using oxidized cast iron and grey cast iron. This was not a traditional wootz process.

Some time before 1837, Henry Wilkinson, the famous sword manufacturer, also took an interest in the cause of the pattern. Rostoker and Bronson (1990, 130) claim that Wilkinson was the first European to make an explicit correlation between the visible crystals on the surface of an unforged wootz steel and the patterning on the finished sword. However, Wilkinson contributed to our understanding in further ways. He published in the Journal of the Royal Asiatic Society a request for materials and information on production of Indian wootz steel (1839, 383-389). Apparently, he obtained samples from Cutch, on the India-Pakistan boarder, and also from Salem, southern India. After performing some experiments Wilkinson (1839, 389) concluded that only the wootz from Cutch produced "jowhar" or watering. He compares the steel from Cutch to that from Salem. He says that the Salem sample had only a slight indication of a pattern and the steel was inferior, but the sample from Cutch was of excellent quality and both the "cake" and finished object exhibited a Damascus pattern. Wilkinson, therefore, makes a direct correlation between the use of the word "jowhar" at Cutch, signifying a Central Asian connection. Abbott also made the observation that patterned steel was being produced in northern India and there the producers called that product pulad.

It seems, therefore, that wootz becomes associated with the Damascus pattern before the 1820s but the association is not made from ethnographic observations but via European replication experiments. It shall also be noted that the only ethnographically produced crucible steel that made a "quality" Damascus pattern was from northern India/Pakistan, which is fundamentally Central Asian, not from southern India, which is associated with the term wootz. In addition, in northern India, the use of the word pulad indicates Persian connections in the process and further associating Central Asia with the presence of Damascus steel swords.

Summary of Russian Research

Crucible Damascus steel research was also in progress in Russia but with a significant difference to the English research; the initial information was based on Central Asia processes and actual swords. In Russia during the 18th century, Tsar Alexei Mihailovich sent three artisans to Astrakhan to learn the art of forging Damascus steel (Panseri, 1963, 17). However, what happened after they were sent there was not recorded (Levykin, pers com.). The most notable researcher was Pavel Petrovich Anosov (1799-1851) who attempted to improve steel and replicate the Damascus steel pattern. Exactly when Anosov started his crucible steel research is not known but it was after 1819 when he was made supervisor of the damascene weapons department of a small arms factory in Zlataoust. These were the decorative types of damascene weapons not the crucible steel variety. Apparently by the mid 1830s Anosov had already mastered the crucible variety.

There are many fallacies written about Anosov. A common one is that he "travelled to India or Arabia disguised as a dervish or muffled up in a burnoose and mixed with motley crowds in Eastern bazaars, looking for the best Eastern blades and trying to obtain the secret of their manufacture by making his way cunningly, using deception and bribery to enter the workshops of Eastern experts" (Bogachev, 1952, 48). Anosov did not learn how to produce Damascus steel by deception and bribery but rather through scientific experiment. A text written by Bogachev in 1952 for the 150th anniversary of the death of Anosov and translated from the Russian into English in 1986 is used here as the primary source of information about Anosov's work. Additional information was learnt while attending a conference on the 200th birthday anniversary of Anosov in Zlataout where he conducted most of his research, and by observing firsthand blades produced by Anosov.

That Anosov knew about other scientists alloying research is indicated by the fact that he was aware of the Royal Asiatic Society's call for information on crucible steel in India (Wilkinson, 1839, 388). Even if Anosov was aware of others' research it does not reduce the credit he deserves for the information he provides. Anosov also claimed that his research would be more successful than the British research because he was studying actual swords that exhibited a pattern, rather than concentrating on imported "cakes" or ethnographic reports (Bogachev, 1952, 49).

Anosov thought that the characteristic external macrostructural pattern of the typical Damascus blade was the result of the blades microstructure (Bogachev, 1952, 47). To advance his Damascus steel research, in 1831 Anosov was the first to use a microscope to study the metallurgical structure of his sample. This is three years before Sorby, who is usually credited for being the first (Smith, 1968, 218).

Anosov documented four methods to produce crucible Damascus steel with the characteristic pattern (see below). Anosov also discussed the characteristics of the shrinking phenomenon and the necessity of slow cooling for crystal growth. He also discussed the necessity of repeated forging at low temperatures and the different methods of producing different patterns.

Anosov gave three blades to James Murchison, a British Naturalist who was exploring in Russia. The author discovered, in a letter written to Faraday by Roderick Impey Murchison (James, 1996, letter 1432), that Anosov sent a sword to Faraday in appreciation of Faraday's research. The sword has been located in the Faraday Museum, Royal Institution, London. The tip of the blade does indeed show a fine Damascus pattern but the remainder of the blade appears to have been cleaned but not re-etched, and therefore, the pattern is not visible. On the back edge of the sword there is engraved, in Russian, "From Anosov to Faraday 1842 Zlataoust". The British Geological Survey in Keyworth, England houses a second blade belonging to Murchison. The location of the third sword is unknown.

It may be suggested that the "legend" of Anosov and his crucible Damascus steel was an inflated product of Soviet propaganda or Russian nationalism, but this is not so. There are accounts of British explorers who met Anosov in Russia. Their praise of him as a good-hearted man and a brilliant metallurgist even exceeds the Russian descriptions. In 1847, while Anosov was stationed in Zlataoust, Thomas Witlan Atkinson visited him. Atkinson was a British artist and explorer spending seven years travelling around Siberia, Mongolia and Central Asia. He describes Zlataoust as the "Birmingham and Sheffield of the Ourals [*sic*]" (Atkinson, 1858, 117). He also describes General Anosov as "one of the most skilful and ingenious metallurgists of the age" (Atkinson, 1858, 117-118). Atkinson saw many of Anosov's Damascus steel blades and he urged Anosov to publish his experiments and findings sooner rather than later, but unfortunately Anosov only lived long enough to publish an abridged version of his research. This paper "On the Bulat" was published in the Russian <u>Gorny Journal</u> in 1841. It was soon to be translated into French and German in 1843.

Another British explorer who befriended Anosov was Major James Abbott of the Honourable East India Company's Bengal Artillery. His descriptions of crucible steel and Damascus steel in India together with Anosov's descriptions of how to produce Damascus steel are a useful study because they connect the products of Anosov's replication experiments to ethnographic observations of traditional methods of producing Damascus steel.

Although Abbott did not fully agree with Anosov's classification of Damascus steel or his estimate of the quality of different types, he did think that Anosov produced high quality Damascus steel swords. Abbott stated (1856, 347) "So far Colonel Anossoff [*sic*]; a man whose researches in this department of science have enabled him to revive the natural damask, in a degree of perfection which I have never observed in the workmanship even of the ancients, and which certainly cannot be approached by fabrics of any European nation at present existing". Anosov inspired Major Abbott so much that in his book he includes a section on Damascus steel written by General Anosov before his own discussion of his own observations of Damascus steel.

Although Abbot's discussion of swords was reprinted in the Journal of the Asiatic Society and has been briefly mentioned by some scholars, the complete comments from his "*Narrative*" (1856, 341-358) surprisingly have not been discussed in any depth. Abbott by his own admission, since an early age, had been fascinated by everything to do with arms and took every opportunity to study them. He studied weapon collections both in Europe and Russia. He also had swords from Egypt and Syria. He says that the art of making Damascus steel had been lost in Damascus by his time. He observed them being made, both by traditional method in India, and by replication experiments performed by Anosov in Russia. Although his observations were not systematically recorded, Abbott discusses many different types of swords, where they are forged, their names, quality, colour, and type of pattern. He also provided a detailed account of the forging of a blade as he witnessed it in north India. His records are particularly significant because they are the only account of someone who saw and recorded the appearance and quality of replicated Damascus steel swords as well as those made by traditional methods.

Recent Experiments

Although the above discussion makes it apparent that methods of reproducing Damascus steel were known during the 19th century, throughout the 20th century scholars still attempted to "rediscover" it. However, the assumption is that the technique was "lost" due to a lack of examination of primary research, rather than a true "mystery". Rostoker and Bronson had it back-to-front when they wrote in 1990 (p. 132) "Even though we seem to have reasonable explanations for the origin of the damascene pattern, no one has yet replicated the true Damascus sword". We have seen this is not true, as Anosov had replicated true Damascus swords. Recently there have been new discoveries about the mechanisms that cause the appearance of the "Damascus" pattern.

Anosov documented four different crucible charges and processes that he used to produce crucible steel:

1) Direct reduction from the ore;
2) (Co)-fusion (or decarburization) of cast iron with iron oxide;
3) Melting and casting steel into a mould and;
4) Reacting iron and carbon (carburization) (Bogachev, 1952, 53-65).

According to Anosov all of these methods produced crucible steel with a Damascus pattern. Crucible charges and processes employed in all other ethnographic accounts (Chapter 2), translations from ancient texts (see above), or replication experiments of crucible steel, can be placed into one of Anosov's four categories, although the details of charges and processes vary.

Studies and attempts to replicate Damascus steel are still being performed, such as by the blacksmith Al Pendray and Richard Furrer in America (pers. com.), and Mike Peterson in Australia. Recent attempts have been conducted by the team of J. Wadsworth and O. D. Sherby (e.g. 1992, 165-172), and by the team led by J. D. Verhoeven (e.g. 2001). Both teams claim to have rediscovered the process of making Damascus steel (Verhoeven, 2001; Sherby and Wadsworth, 1985, 112-120). Sherby and Wadsworth (1985, 112-120) heated steel (1.7%C) castings to 1,150^{O}C for 15 hours and then slowly cooled the steel at a rate of 10^{O} C per hour. The steel was then reheated to 800^{O} C and rolled to simulate forging. They reported that a Damascus pattern was visible in the finished product and therefore was a rediscovery of the Damascus steel process. Their method is comparable with Anosov's third method; however, Sherby and Wadsworth used more modern equipment than Anosov had. The use of steel casting and the rolling of the steel are inconsistent with traditional historical steel production methods. It is more appropriate to state that Sherby and Wadsworth had found a method of producing a Damascus pattern under modern laboratory conditions using modern technology.

Verhoeven, however, used more traditional methods (see below). Verhoeven *et al.* (e.g. 2001) primarily used ethnographic reports of wootz production as the inspiration for their experiments. Depending upon the experiment, they used leaves, glass, oyster shells, and steel or wrought iron in the crucible charge. Essentially their experiments were based on a carburization process. His experiments have contributed to our knowledge of possible crucible charges and the factors needed to produce the characteristic Damascus pattern.

There is a consensus of opinion that the ingots have to be annealed prior to forging (e.g. Verhoeven and Pendray, 1992; Furrer, pers. com). According to Verhoeven and Pendray (1992, 210) the as-cast ingot was "hot short" due to microsegregation of phosphorus and sulphur. Heating the ingots for 11 hours at 1200^{O}C produced a ductile outer shell encasing the "hot short" interior. Ethnographic reports also report annealing of ingots (e.g. Voysey, 1832).

The Production of Crucible steel and the Damascus Pattern

There are two fundamental factors that will profoundly influence the final characteristics of the steel product: the crucible charge and the forging method. The materials and methods used to produce and forge the ingot will directly affect whether or not a pattern can be produced. Modern replication experiments, historical and ethnographic accounts demonstrate that there are many possible ingredients that can be used for the crucible charge to produce a crucible steel ingot. They have also determined particular factors which are necessary to produce a pattern.

Al-Beruni stated that farand (the Damascus pattern, see below) was not the result of industry and design, but was an accidental product (Said, 1989, 218). Curiously, Wilkinson (1937, 193) made a similar statement a thousand years later, "...the figure of the genuine ancient and modern Damascus sword-blades is the result of nature, and not of art". More recent research by various scholars has determined the factors which affect the formation of the pattern and it is now known that the pattern is indeed the result of the nature of steel, although a certain amount of "art and industry" of forging is also required.

Essentially crucible steel can be produced from an infinite number of possible crucible charge ingredients containing iron and carbon. The presence of minor and trace elements in the crucible charge, via the source of iron, carbon or additional substances added to the charge, will also affect the steel ingot. These elements can affect the forging of the ingot (e.g. in rendering it "hot short" due to phosphorus) in addition to the performance and appearance of the final product (see below).

The percentage of the carbon content of the crucible steel is significant for the creation of different types of patterns and the performance of the blade (see below). Hypoeutectoid (< 0.8% C) and hypereutectoid (> 0.8% C) steel can produce a pattern, but the microstructure and, therefore, the pattern will be noticeably different. Hypoeutectoid steel will produce a banded pattern (e.g. Sham pattern), however, the most characteristic Damascus steel patterns (e.g. Kara Khorasan pattern) is produced from hypereutectoid steel.

Hypoeutectoid ingots produce ferrite-pearlite banding. A factor in the production of the banding is the presence of elements, which during the solidification of the liquid ingot, remain in the interdendritic region (Samuels, 1980, 129). Pearlite will form in the interdendritic band, possibly influenced by the presence of manganese. According to Samuels (1980, 129) the dendrite itself is composed primarily of ferrite and very slow cooling will produce bigger bands.

Studies, primarily lead by Verhoeven (e.g. 2001) have found that the formation of the pattern in hypereutectoid steels is due to the alignment of globular/spherical cementite in the interdendritic zones. The cementite aligns because of the presence of impurity elements present in the interdendritic zone. Verhoeven *et al.* (1998) determined that elements such as vanadium and molybdenum, even in quantities as low as 0.003%, promote the alignment of cementite. Other elements, which also promote banding, are chromium, niobium, and manganese (Verhoeven *et al.*, 1998, 63).

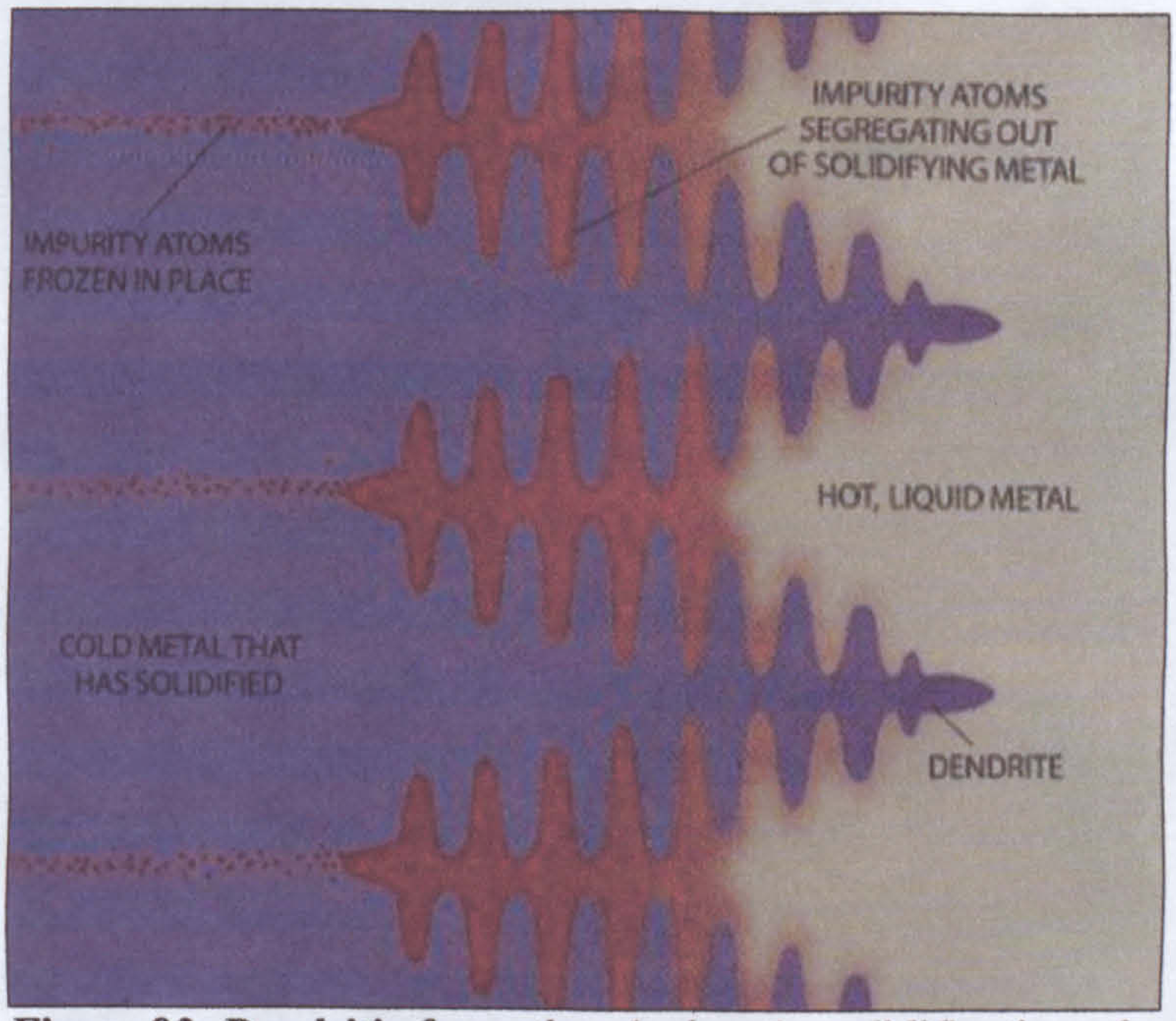


Figure 93: Dendritic formation during the solidification of an ingot. (From Verhoeven, 2001, 65)

The effect of the cooling rate on the forging of the ingot and the resulting pattern has not been studied in any depth. Verhoeven and Jones (1987, 170) note that cementite at the prior austenite grain boundary form during slow cooling, whereas faster cooling rates promote Widmanstätten cementite. Richard Furrer (pers. com.) noted that during his replication experiments quickly cooled ingots were easier to forge than slowly cooled ingots. This is probably the result of the different cementite locations. Verhoeven (pers. com.) stated that the cooling rate of the ingot is not a necessary factor for the formation of the pattern. However, it seems reasonable to assume that the cooling rate affects the appearance of the pattern. This is because the faster the ingot cools, the smaller the dendrites are, and therefore, the closer the interdendritic zones. The closer the interdendritic zones, the closer the aligned globular/spheroidal cementite are, and therefore, the finer the final surface pattern. Therefore, a blade forged from a slowly cooled ingot would have a coarser pattern than a blade forged from a quickly cooled ingot, assuming that the blades require a similar amount of forging. In addition, Verhoeven and Jones (1987, 177) suggest that the grain boundary cementite grows coarser with each forging cycle, opposed to the Widmanstätten cementite, which becomes finer. It is the large cementite particles responsible for the thicker "thread" of the Damascus patterns. The extent of forging and consequently the extent of deformation of the dendrites would also affect the fineness and appearance of the pattern. The influence of the cooling rate was also noted by ethnographic accounts. Bronson (1986, 38) states that many ethnographic observers suggested that the Damascus pattern "is an effect of cooling the original crucible contents at an extremely slow rate". However, Bronson (1986, 40) then continues with the supposition that this "is not well supported by the data on actual wootz making". It seems that here he is assuming that wootz steel will make a pattern, although he reported that there are no firsthand sources that it yielded a Damascus structure. Therefore it seems likely that the fineness or coarseness of the final pattern would depend on the cooling rate of the liquid steel in addition to the amount of forging. A slowly cooled ingot could make a coarse pattern or, if forged for a long period, a fine pattern, but a quickly cooled ingot could never make a coarse patterned blade but only a fine patterned one.

Verhoeven and Pendray's (1992, 210) experiments found that the as-cast ingot was "hot short" due to microsegregation of phosphorus and sulphur. Although few ancient steels contain sulphur, they often contain phosphorous. Since the ingots solidified from a liquid, they have areas particularly high in phosphorus appearing as the iron-carbon, phosphorous phase steadite rather than being evenly distributed, thus the ingots are "hot short". Whether ancient blades were also "hot short" and if this decarburization procedure would have been needed if the crucibles cooled slowly in the furnace or is necessary for all crucible steel is uncertain, however, the crucible steel blades examined in Chapter 4 did contain areas with around 0.1% P. The findings by Verhoeven, that the crucible steel ingots were "hot short", are important for three reasons:

1) It supports the fact that Moxon among others noted that "hot shortness" was a feature of crucible steel.
2) Being "hot short", the blades required a different forging technique than used for other types of steel.
3) The low temperature forging would produce spheroidal cementite.

The phosphorous in the ingots caused the ingots to be "hot short" and therefore they had to be forged at low temperatures. Verhoeven (2001, 65) found that during forging at the necessary low temperatures, below the austenite transition temperature (see Figure 94), the cementite collects in the interdendritic regions, perhaps nucleating on the impurity elements, which are concentrated in the interdendritic regions. The austenite transition temperature (A_{cm}) is the temperature at which ferrite and cementite begin to separate during slow cooling (Samuels, 1980, 43). The austenite transition temperature depends upon the elemental composition of the steel, particularly the carbon content. The transition temperature begins in the region of 730^{O}C, around the eutectoid composition (0.8% C). The austenite transition temperature increases with the carbon content until the carbon content reaches around 2% (cast iron) where the temperature is over 1100^{O}C (see Samuels, 1980, 43).

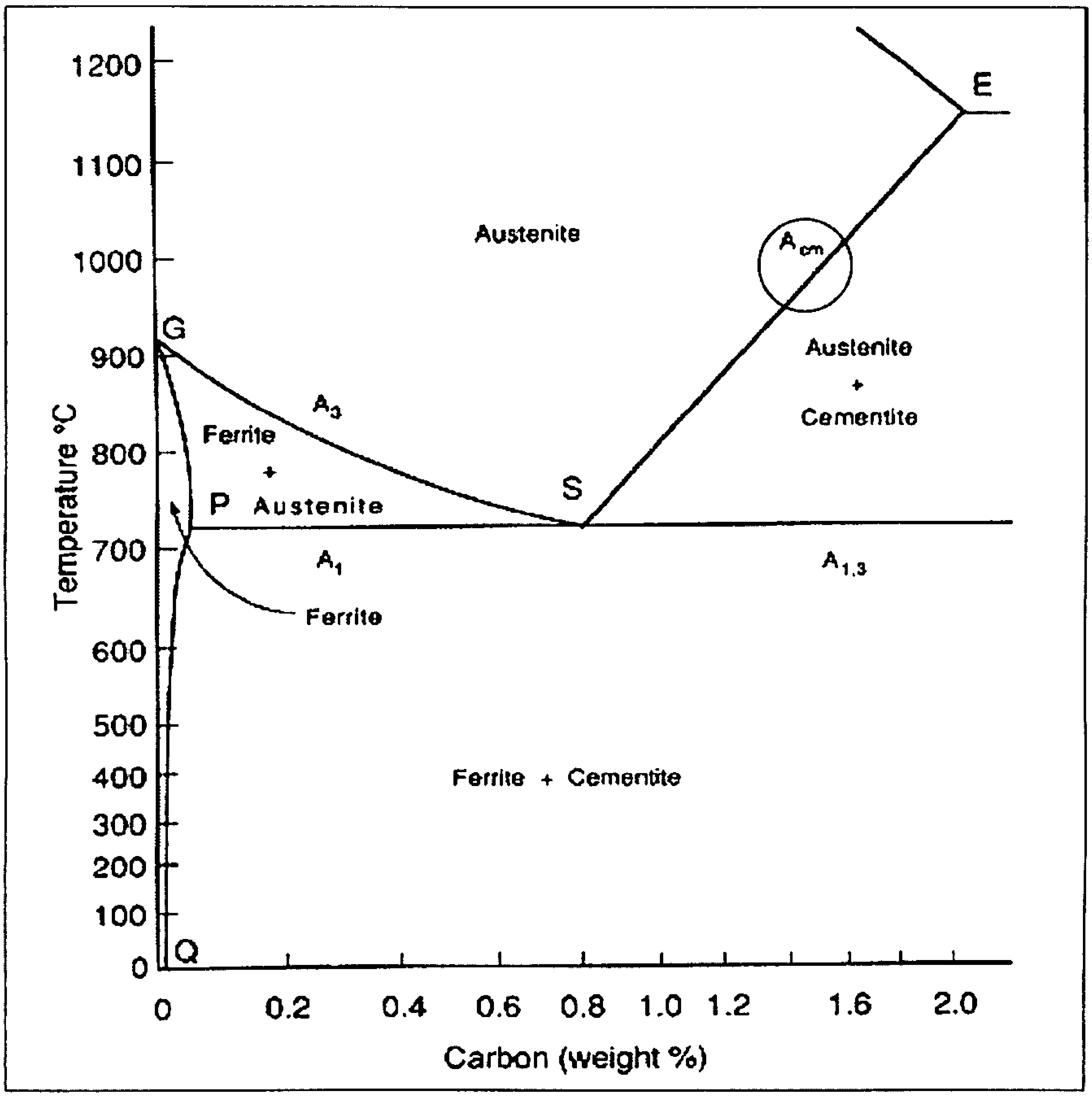


Figure 94: The steel portion of the iron- carbon diagram
(From Wagner, 1993, 270).

The time and temperature of the forging are major factors in the formation of the pattern. Verhoeven and Pendray's replication experiments heated the blades to 50°C below the austenite transition temperature and then forged the blade while it slowly air-cooled to around 250°C below the austenite transition temperature (Verhoeven, 2001, 64-65). They record that initially the carbides are randomly distributed but after additional heating and forging at these temperatures the cementite began to align. The more cycles they performed, the more distinct the banding became.

In order for the pattern to be readily observed on the surface of the blade, the decarburized and oxidized layer had to be ground off, the blade had to be cleaned and polished before it was etched. Wilkinson records that wood-ashes and water were used in India, or chalk and water to remove any surface grease (1837, 191). Other materials used to clean the steel include dry lime with water and tobacco ash (Sachse, 1994, 83). To etch the blades, Wilkinson (1837,191) discusses the use of dilute nitric and sulphuric acids at Cutch. He also records that a better effect is produced when the blade is immersed in a bath of copper sulphate in water for ten to thirty minutes

(Wilkinson, 1937, 190-191). Sachse (1994, 84) refers to the use of ferric sulphate and ferrous sulphate to etch the blades. The etching reacts preferentially to the iron and carbide regions and the effect depends on the type of etchant used and the amount of time it reacts with the metal. According to Verhoeven and Jones (1987, 155) the white component (a.k.a. threads, see Classification of Damascus Patterns below) of hypereutectoid Damascus patterned blades is the cementite. On hypoeutectoid blades the ferrite is the white or lighter component. The darker "background" colour (see below) is often a form of pearlite which appears darker, or having a pearl–like appearance, hence the name. However, which phases appear lighter or darker also depends on the microstructure and the etchant used.

In summary, the formation of the pattern particularly in hypereutectoid blades is due to the interdependent relationship between the elements contained in the crucible steel ingot and the forging process. The presence of phosphorous in the crucible steel dictated the low forging temperature. In turn, the low temperature forging produced spheroidal cementite. The presence in the ingot of the trace elements such as vanadium, molybdenum, chromium, niobium, or manganese promote the alignment of the spheroidal cementite in the steel, thus producing the Damascus pattern when etched. The relationship between the elemental composition of the ingot and forging method associated with hypoeutectoid blades has not been studied in detail. However, the presence of elements such as manganese promotes the growth of pearlite in the interdendritic region, whereas the dendrite is composed of ferrite. Slow cooling of the ingot will produce bigger bands and these bands can be observed when the blade is etched.

Studies of Damascus Steel Blades

There have been eighteen metallographic studies of Damascus steel blades, and seven of these blades were reanalysed by Verhoeven *et al.* (1998, 58-64). Two daggers and four swords were first analysed by Zschokke (1924). These blades were from the collection of Henri Moser and are now in the collection of the Berne Historical Museum Switzerland. A blade attributed to Damascus and estimated to be about 400 years old was originally analysed by Voigt and Abu-Samra using Neutron and Gamma Activation (1965) and was also reanalysed by Verhoeven *et al.* (1998, 63). The evidence for the blade being from Damascus and the age was not presented in any report. Dr. Figiel provided two blades for study, one recently purchased in Rajasthan (Verhoeven and Peterson, 1992, 336). The second blade Verhoeven *et al.* refer to as Kard because it is a knife in the style of a Persian Kard (Verhoeven, 1998, 63). Verhoeven *et al.'s* (1998) blade called Old B is a Damascus steel blade of unknown origin (Verhoeven and Pendray, 1992, 195). Piaskowski analysed two Damascus blades that he obtained in Damascus (1978, 5). Panseri (1963) analysed two swords. Blade #1 exhibits a typical Kara Khurasan pattern. Blade #2 is attributed to the 16th –17th century and is signed Asadollah. Maryon (1960) studied a 17th century Indian dagger which has a Damascus pattern. France-Lanord examined a fragment of a blade from Iran but the date of manufacture is unknown (1969, 122-126). Belaiew also analysed two blades but neither blade had an original provenance (1918, 1921). Two blades from the collection of Richard Furrer, an 18th century Indian Talwar sword and a mid 18th century Persian Jumbiya dagger, were examined by Harsh (2001). The largest problem associated with all of these blades is that they have no firm date of manufacture or provenance.

Although each of the blades exhibited a Damascus pattern, the microstructures were not the same. The Zschokke blade #8 is made of hypoeutectoid steel and would have exhibited a different pattern as a result of ferrite-pearlite banding. All the other blades were made of hypereutectoid steel and the pattern was formed by the alignment of globular/spherical cementite in a ferrite/pearlite matrix. Verhoeven *et al.* (1998) summarise the microstructure of high quality hypereutectoid blades with a Damascus pattern as consisting of bands of cementite particles around 6 μm in diameter (Verhoeven *et al.*, 1998, 59). The bands are parallel to the forging plane and have a "characteristic spacing in the 30-70 μm range and are contained in a steel matrix" (Verhoeven *et al.*, 1998, 59). The microstructure of the steel matrix varies but often consists of pearlite and DET (divorced eutectoid transformation). DET occurs when the steel is cooled very slowly and indicates that the blades were air-cooled. The DET produces a structure of cementite in a ferrite matrix. The edges contained pearlite because they cooled faster than the areas closer to the middle of the blade. Verhoeven *et al.* (1998, 61) noted graphite stringers in Zschokke's sword #7 (hypereutectoid). Graphite can form when steel is heated for long periods at subcritical temperatures (Samuels, 1980, 231). France-Lanord illustrates the microstructure (1969, 123) and at x100 magnification the blade showed the mottled surface observed on the crucible steel swords (see Chapter 3). The microstructure is spheroidal cementite in a lamellar pearlite matrix. The blades reported by Harsh (2001), the Talwar and a Jumbiya, have a banded spherical/globular cementite but the matrices are different. The Talwar has a fine pearlite matrix with cementite at the prior austenite grain boundaries, whereas the Jumbiya has even a finer matrix but no grain boundary cementite. The microstructure of the Piaskowski blades consists of cementite in a sorbite matrix but the back of the blades also contains ferrite (Piaskowski, 1978, 15), which is a product of the DET. Sorbite is an earlier name for what is often now called fine lamellar pearlite but was also used to refer to tempered martensite (Samuels, 1980, 26). Piaskowski (1978, 5) notes that the aligned carbides are thinner in sword #2 and thus they produced a finer surface pattern. Piaskowski (1978, 6) also noted that in the back of his blade #1 there was a non-metallic slag inclusion. Unfortunately the elemental composition of this inclusion was not determined. Piaskowski (1978, 10) noted that Abbot (1847) remarked that during forging, the back of the blade was formed from the upper part of the ingot. Evidence from archaeological remains indicates that slag gathered at the top surface of the ingot (see Chapter 1) therefore the slag was probably trapped in the upper part of the ingot, rather than unreacted crucible charge.

Classification of Damascus Patterns

The term Damascus swords or Damascus steel has become synonymous with blades or iron/steel objects that have any surface pattern. Historically there are many different names for blades that have specific patterns or shapes, sometimes reflecting different workshops, geographic areas, craftsmen, quality or surface appearances. A comprehensive study of the many different names and patterns is beyond the scope of this research because it would be too large an undertaking. However, characteristics and factors for a classification system are discussed. Replication experiments have shed light on the mechanisms that determine the microstructure and cause the pattern to appear. By comparing microstructure and the mechanisms that caused the microstructure, together with the name of the surface pattern, a preliminary classification system for possible types of crucible steel, some of which have patterns, can be proposed. Similar methods of classification by attributes have been performed for pottery studies (see Rice, 1987, 274-288). The typology of the blades' shape is not discussed here because all shapes can be made from crucible steel, and theoretically, any pattern can appear on any blade.

The first classification of swords was performed during the 9th century AD by al-Kindi. A new detailed translation and annotation of al-Kindi's text is forthcoming by Allan, Gilmour, and Hoyland (Allan and Gilmour, 2000, 192) and therefore al-Kindi is not discussed here in detail. Anosov produced the first modern classification of the various Damascus steel patterns during the mid 19th century (Bogachev, 1952, 39-40). Piaskowski (1976, 239) further divided Anosov's classification. Other classifications have been presented, such as the discussion found in the exhibition catalogue Weapons of the Islamic World (1991). The most useful recent discussion is found in Sachse (1994, 72-73) who discusses the different patterns and also illustrates them. These classification studies, along with the mechanisms that cause the pattern and the different varieties, shed additional light on the types of patterns that may have been available in the past, in addition to their possible appearance and quality.

Anosov listed five patterns (Piaskowski, 1976, 238). The different types were illustrated by Sachse (1994, 73) and are reproduced here (Figures 95-100).

Table 31: Pattern and Names

1	Stripy Damask	Sham (Syria)
2	Water Damask	Damascene
3	Wavy Damask	
4	Chequered, mottle, network, or woodgrain Damask	Kara Khorasan Kara Taban Persian
5	Ladder (vertebrae) Damask Mohammads Ladder, Ladder of the Prophets, Jacobs Ladder, 40 steps	Kirk narduban Kirk ner deban Rose Pattern

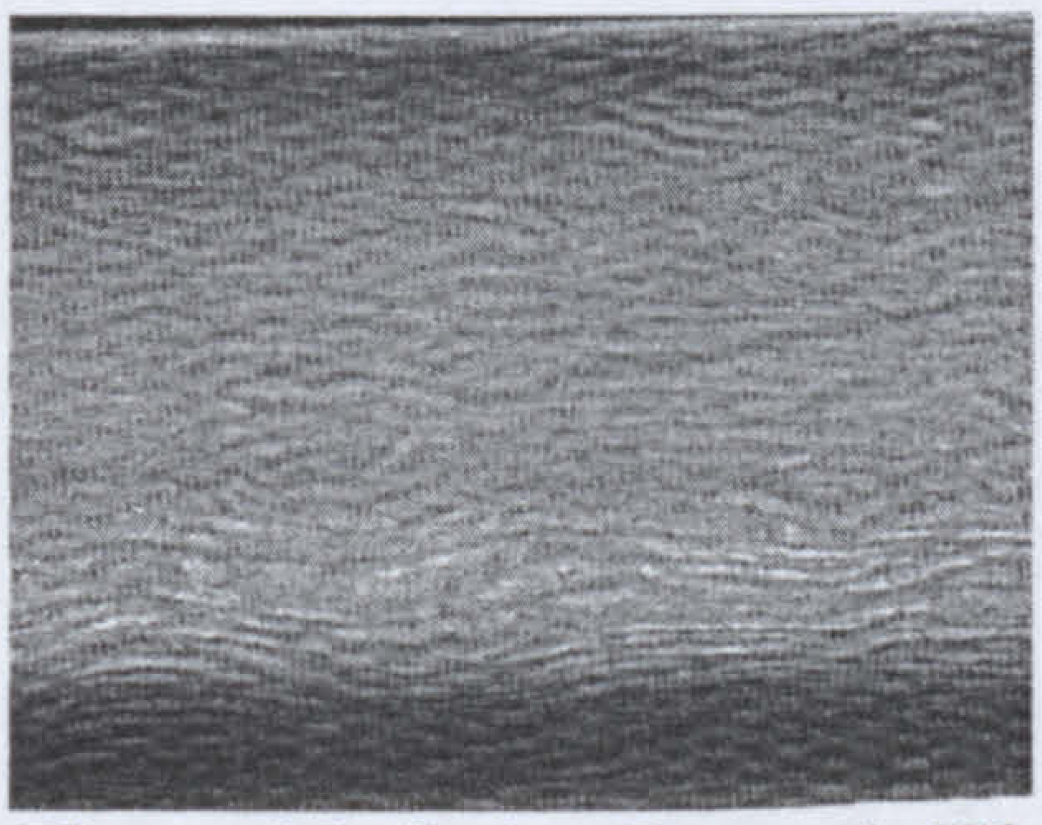


Figure 95: Stripy Damask (Sham)
(Sachse, 1994, 72).

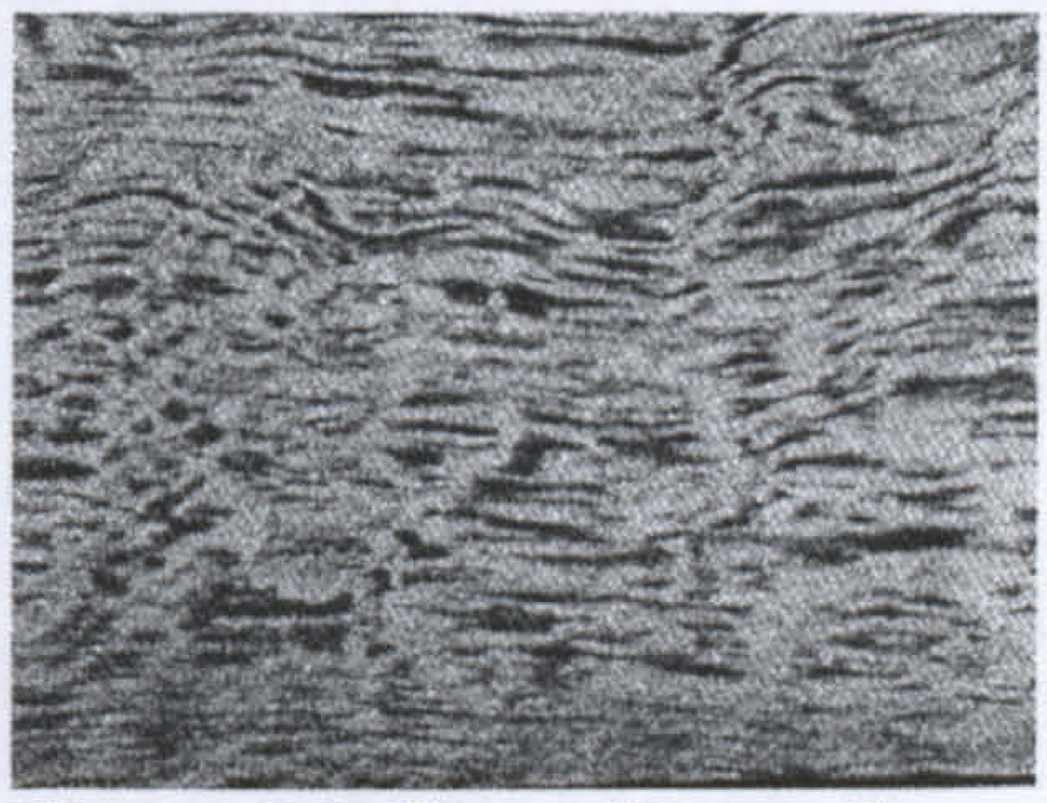


Figure 96: Water Damask
(Sachse, 1994, 72).

Figure 97: Wavy Damask
(Sachse, 1994, 72).

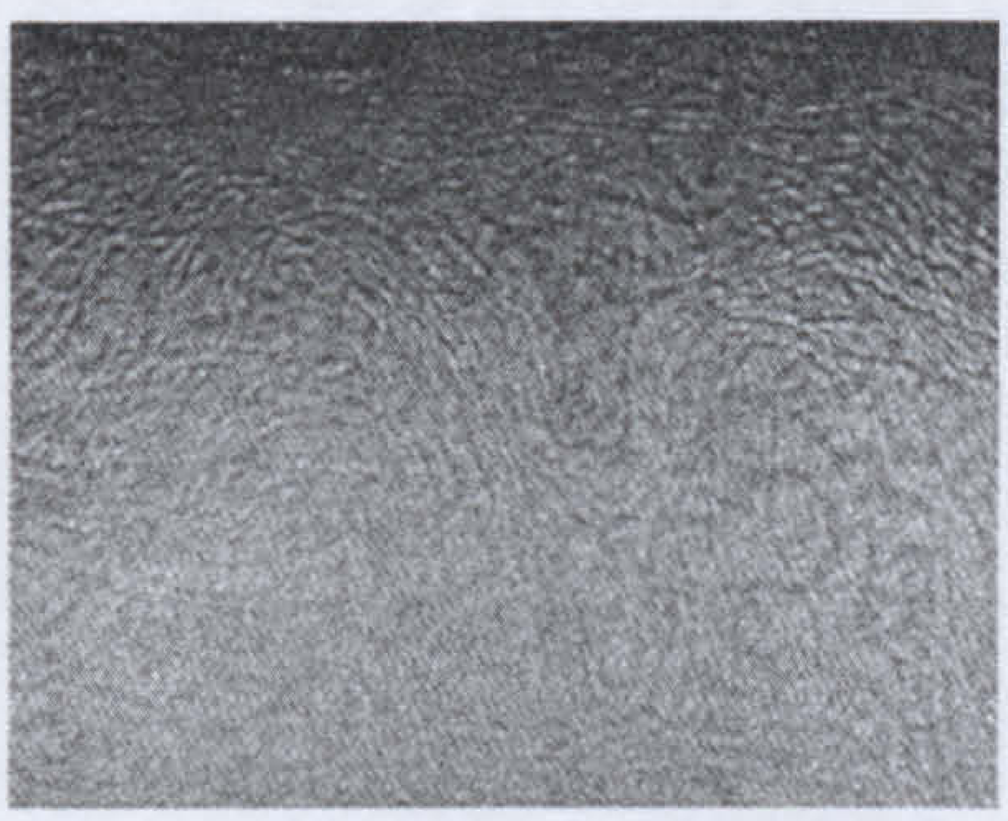


Figure 98: Mottled Damask
(Sachse, 1994,73).

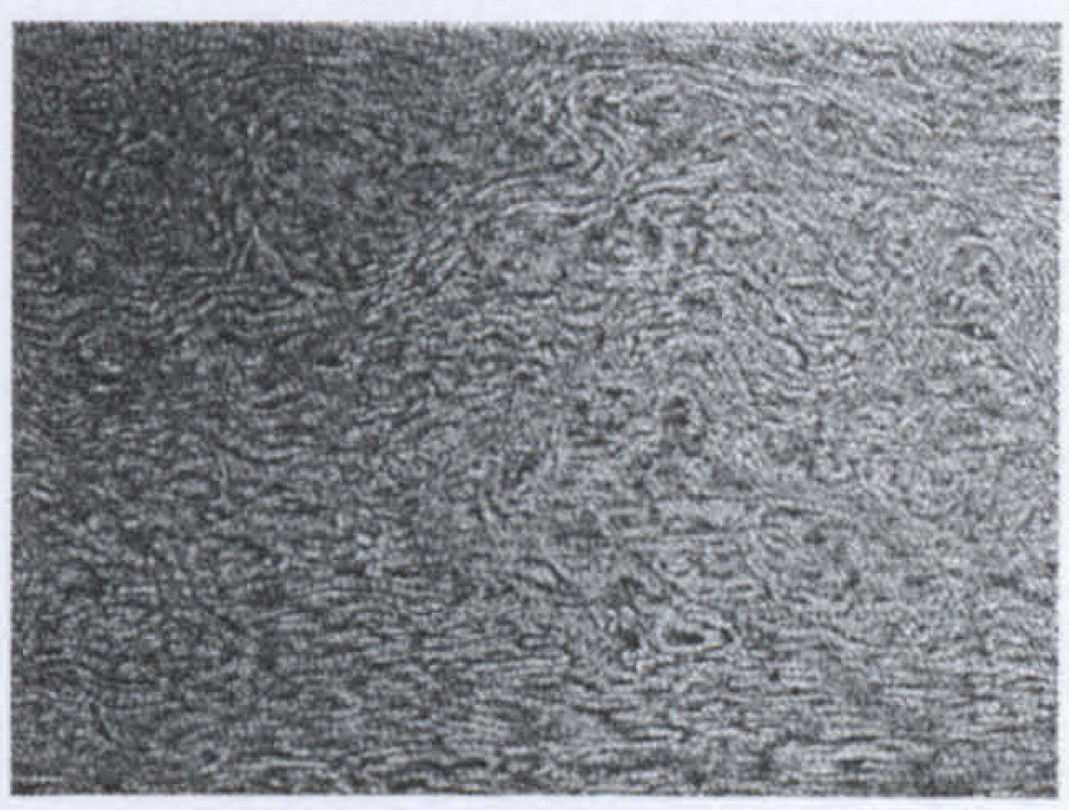


Figure 99: Mottled woodgrain
(Sachse, 1994, 72).

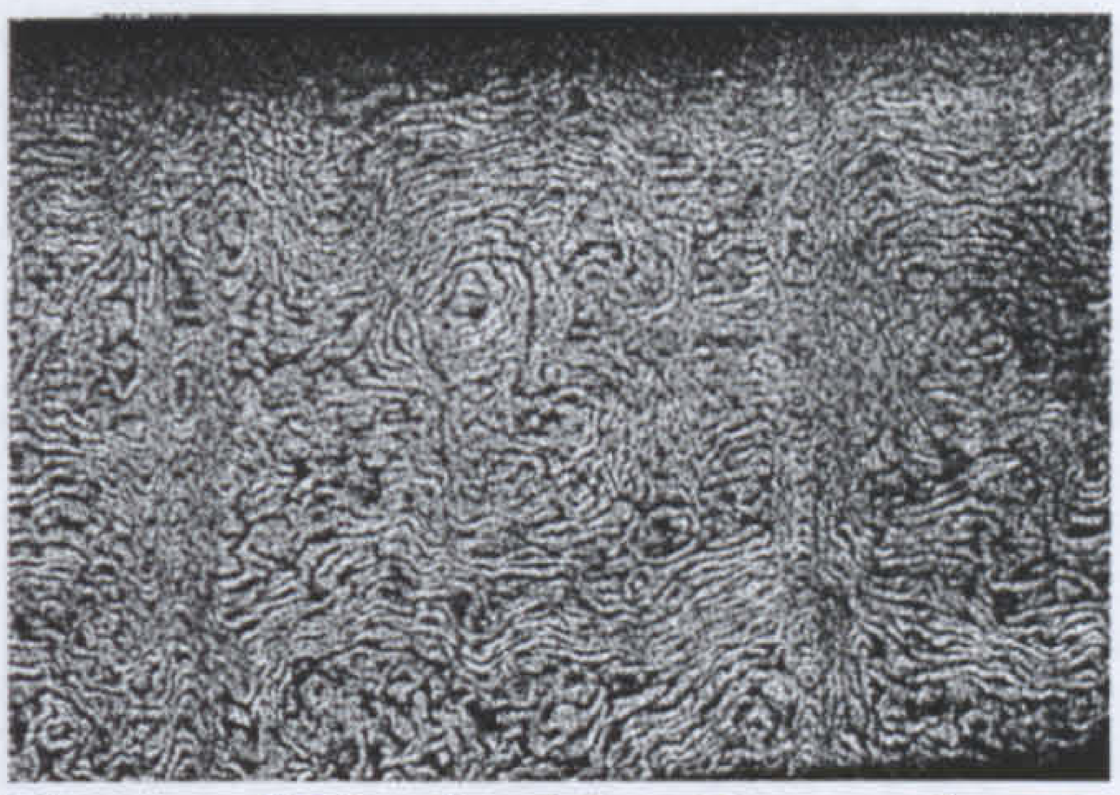


Figure 100: Ladder Damask
(aka Mohammad's ladder, 40 steps)
(Sachse, 1994, 72).

The first two groups of patterns, stripy and water Damask, are made of hypoeutectoid steel. The pattern in formed by ferrite-pearlite banding. Swords with the stripy Damask are known as Sham, named after Syria. In the Weapons of the Islamic World exhibition catalogue (1991, 17) these "soft Damask" blades fall under the Damascene style of decoration and they are described as smooth rust resistant blades with soft, stippled surfaces and generally a light grey colour. Sachse (1994, 73) states that this pattern is found in the earliest blades, although there is no evidence for this.

Verhoeven does not consider these hypoeutectoid steel blades to be exhibiting a true Damascus pattern, however, this is misleading because the blade would have been made of crucible steel and exhibited a pattern. While the mechanisms that cause the pattern in hypoeutectic and hypereutectic blades are significantly different, the method, which would have been used to produce the ingot, would have been the same in antiquity; particularly as only a few grams less of carbonaceous material could have made the difference between producing an ingot with more or less carbon. Blades made of hypoeutectic crucible steel and exhibiting a pattern are a distinct type of crucible steel.

The other three groups, wavy, chequered, and ladder Damask, are made of hypereutectoid steel and the pattern is caused by the alignment of cementite (see above). When the blade is etched the cementite appears as the light coloured threads whereas the background is usually dark. The ladder pattern is in effect a sub-category of the hypereutectoid steel. Creating groves or holes in the surface and then forging or hammering creates the decorative patterns such as the Ladder and Rose. This decorative method has been discussed by a number of scholars (e.g. Sachse, 1994, 75; Figiel, 1991, 74). The first description of these grove patterns comes from al-Kindi who wrote that the Khorasani swords were made from Khurasani iron called *muharrar*, which were covered with knots made by a chisel, and had a black watering (Allan and Gilmore, 2000, 192). Muharrar appears to be the name of the deliberate pattern such as used to produce the Rose or Mohammad's Ladder pattern. Allan and Gilmour (2000, 203) also noted this interpretation.

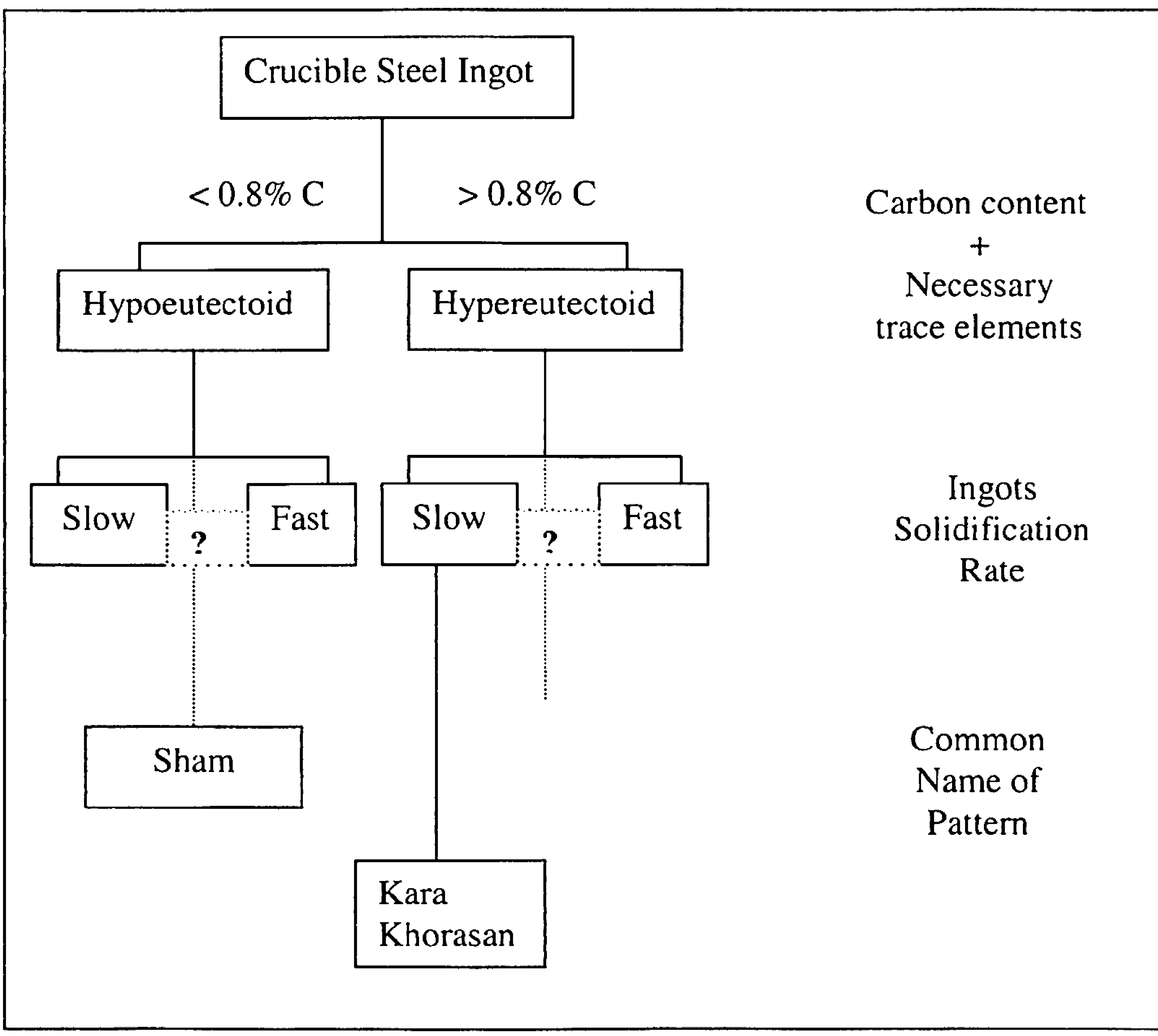


Figure 101: Flow chart of possible patterns based on microstructure.

Anosov (Bogachev, 1952, 40), Piaskowski (1976, 239), and Sachse (1994, 73) further divided the classification by the fineness of the threads, the colour of the threads and the colour of the background. Early Islamic authors, al-Kindi and al-Beruni also noted these attributes. The five attributes, which are used to classify the patterns, are as follows:

1) **Carbon content**
2) **Threads** (and grades)
   - Thin > 20 threads in 10 mm
   - Medium about 15 threads in 10 mm
   - Thick < 10 threads in 10 mm
3) **The colour of the threads**
4) **Colour of the background**
5) **Sheen**

The first attribute is the carbon content of the ingot. If the carbon content of the steel is under 0.8% the steel is hypoeutectoid, above 0.8%, hypereutectoid. This will dictate whether ferrite-pearlite banding or aligned cementite in the microstructure produces the threads observed as the pattern (see above). The threads are the light and dark areas of the blades. Those that exhibit the darker more prominent threads are said to be the most precious blades (Piaskowski, 1976, 238). These threads are probably cementite bands in the hypereutectoid blades. The longer the blade is forged, the clearer the appearance of the threads. According to Verhoeven (2001, 64-65) more cementite will align in the interdendritic zones the more cycles of forging (e.g. longer forging time), producing clearer threads. The finer grade means that the threads are closer together. Studies, however, investigating the influence of the initial cooling of the ingot and the spacing of the dendrites in relation to the final pattern on the blade have not been performed but it would be expected to affect the fineness or coarseness of the final pattern. The observation that crucible steel ingots studied from India have a very fine microstructure indicating fast cooling and the ingots from Central Asia were slowly cooled (see Chapter 1 and 2) may indeed have affected the final appearance of the blade and the resulting thread grade, depending on the extent of forging. Al-Kindi is perhaps referring to the threads when he mentions the "white of iron" and the "yellow of iron". Al-Beruni states that some swords have narrow designs like the "passage along where ants crawl" (Said, 1989, 217). These perhaps correspond to the finer grade. Others had broad designs that appear like "clouds" or "water" (Said, 1989, 217). These descriptions perhaps correspond to the coarser grade pattern.

The background colour refers to the area between the threads. The forging and etchant would affect the background colour. A completely ferritic background (found in some hypoeutectoid blades) would probably appear different from a pearlite background. The type of etchant and the length of time the etchant was applied for would also influence the background colour. Al-Kindi may be discussing the background colour and the threads in his discussion of the effects of etching. He states that the 'ard is the ground or "the area of iron with no watering" (Allan and Gilmour, 2000, 204). He refers to the "red of ground", "green of ground" and "dark of ground" (Allan and Gilmour, 2000, 204).

The sheen is the lustre, reflectance, or perhaps glittering appearance of the sword. The sheen can be absent (Piaskowski, 1976, 239) or range in colour from reddish to a golden colour, which is the highest quality (Bogachev, 1952, 40). Al-Beruni also mentions the word *barand*, which "is that shine which has farand in it" (Said, 1989, 216), suggesting that *barand* is the sheen, thus the glittering appearance of the pattern. Al-Beruni discusses different *barands*: a green shine is preferred on sword from Yemen and Indian swords, whereas in Mashrafi the white sheen is preferred (Said, 1989, 216). Ethnographic accounts also refer to these features (see Allan and Gilmour, 2000, 206).

The above classification taken primarily from Sachse (1994, 73) does not distinguish between Persian patterns and Indian patterns. According to the Weapons of the Islamic World exhibition catalogue (1991, 18) Indian blades are said to be harder and have finer narrower patterns than the Persian blades (Weapons of the Islamic World, 1991, 17). One type of pattern is called Kirk ner deban (forty degrees Johar) which has fine grey and black incisions and horizontal lines, which are said to resemble a net on the surface of water (Weapons of the Islamic World, 1991, 18). Another pattern is called Kara Khurasan, which typically has a crosswise pattern of fine grey and black inclusions. The difference in fineness must be a consequence of its microstructure. A new classification system based on the microstructure and the names of the pattern is given in Table 32.

Table 32: Classification of Patterns Based on Their Microstructure

Carbon Content	Treads	Decorative Style	Grade		Selected Examples of Persian Style
			Fine	Course	
Hypo-eutectoid	Ferrite-pearlite Banding	Damascene	*Sham*	Water	*Kara Khurasan* *Kara Taban*
Hyper-eutectoid	Aligned Cementite		**Indian**	**Persian**	*Kirk narduban* *Kirk ner deban* *Rose Pattern*

Quality and Performance of Ingots and Blades

Ever since Pliny wrote in the first century AD that the best steel was made by the Seres and the second best was that of the Parthians (Rackham, 1995, 233), the reputation of steel from the East being superior in performance has not diminished. During the 3rd century AD, Zosimos mentions the production of high quality swords by a crucible steel method being used in India and Persia. In the 19th century it was recorded that, "In general truly perfect Damascus blades, while they are capable of cutting soft substances with great ease (such as a wet felt folded several times and placed upon a support), will cut with the same blade, and I should say with almost the same ease, both bone and iron, and this without suffering noteworthy damage" (Crivelli, 1821 in Panseri, 1963, 15). However, there are others who disagree, such as Terry who reported in the 17th century that Indian swords were brittle (Foster 1921 in Bronson, 1986, 25). In addition, Zschokke (1924, 665-658) tested four "Damascus" blades and reported that they were not as hard, had a lower breaking angle, and did not have as good resistance to bending as Solingen steel. The quality of the crucible steel blades, with or without a Damascus pattern, would depend upon the ingot from which it was forged and the forging process.

The shape and appearance of the as-cast ingot can provide information about where the ingot was produced and its quality. Archaeological and ethnographic evidence indicates workshops produced ingots with a certain shape. All known ingots from production sites in India or Sri Lanka are roughly "cake", "puck", or "cone" shaped where as those known from Central Asia are all either "egg" or "elongated egg" shaped (see Chapter 1 and 2), reflecting the internal area of the crucible where the ingot solidified. In archaeological or ethnographic examples, where the ingot was not forged nor extensively corroded, the ingot will still retain its overall shape and, therefore, record the interior area of the crucible.

There is no textual or physical evidence to suggest that the quality or provenance of the steel ingot was judged by its appearance in ancient times. Historical accounts, however, indicate that the appearance of the ingot was used to judge its forging behaviour. Anosov mentioned that the surface of the ingot was either relatively smooth or had a small depression at the centre (Bogachev, 1952, 56). In this depression "crystals of damask steel are clearly visible and mixed up with each other" and that these particular ingots were difficult to forge (Bogachev, 1952, 56). Massalski recorded that cakes with pores on the top surface should be avoided because they will form deep holes on the sabre (Allan and Gilmour, 2000, 538). It is reasonable to assume that in the more distant past one of the factors used to determine the quality of the ingot was its appearance. The shape may have been used to indicate where the ingot was made, whereas the surface appearance may suggest the quality of the steel and forging properties.

The quality of different swords was first noted by al-Kindi. He used the terms, translated as "antique" for good, "modern" for not good, and "not antique but not modern" for medium quality. Al-Kindi said that the terms did not reflect age but quality. There is no consensus of opinion on the quality of crucible steel or Damascus steel either in antiquity or by modern researchers, "Some say the blades were flexible and tough; others conceded that they were stiff and even brittle but extraordinarily sharp..."(Bronson, 1986, 13). The appearance and behaviour of a metal is the result of the microstructure. Before modern times, when elaborate scientific equipment became available, the quality of a blade was judged on external factors rather than microstructure. However, steels made by different methods, with different microstructures, could have similar behaviour properties or hidden defects.

Anosov wrote that Damascus swords were assessed by four "tests":

1) "**Ring**: – the clearer the tone, the better is the quality of steel,
2) **Sharpness of the cutting edge**: - while testing the edge, damask steel must cut a fine silk handkerchief in one stroke,
3) **Strength of the blade**: - on cutting an iron bar, damask steel should not acquire notches,
4) **Elasticity:** - on bending, damask steel should not break and should not become permanently deformed" (Bogachev, 1952, 40).

Al-Beruni also refers to these same characteristics. He refers to qala` swords which have clangour, whereas non-qala' swords "possess an irritating sound" (Said, 1986, 213). Whichever type of swords these were, the passage does suggest that sound was an important feature considered when assessing the quality of the sword. More recently Massalski stated that a sabre should possess a good sound (Allan and Gilmour, 2000, 539). Indeed, the composition of the sword would affect its sound. According to Rostoker and Bronson (1990, 151) iron and steel are used to made musical wire because they have better properties than other metals, such as capacity for tension and good resistance to fatigue fracture. No specific studies have addressed the sounds different types of blades make. Factors that would affect the sound include the shape of the blade and any faults. For example, an internal crack or atomic-scale changes will have a dampening effect (Gordon, pers. com.). Thus, a clear long ring would suggest a quality blade.

The relationship between the sharpness of the blades and the pattern was noted by a number of scholars. Sharpness is primarily due to the presence of cementite in steel, which is hard yet brittle, thus it will cut well but will shatter if struck. Contrarily, iron areas composed of soft ferrite will not hold a sharp edge. Already, al-Beruni stated that the sharpness of farand (the pattern) comes from its hardness, but that it is brittle (Said, 1989, 217). Too many "threads" (i.e. aligned cementite in hypereutectoid blades) would produce a sharp yet brittle edge. Above it was discussed that prominent threads would be formed in slowly cooled ingots, which were extensively forged at low temperatures producing the coarser and clearer pattern.

The ductility of Damascus blades was one feature that distinguished it from other types of steels. Damascus steel blades typically contain spheroidal/globular cementite in a ferrite/pearlite matrix. Metallurgical experiments conducted by Ebner and Maurer (1982) on steel concluded that toughness and ductility coincide with a spheroidization of carbides. They also noted that additional tempering decreases the strength whereas toughness and ductility vary only slightly (Ebner and Maurer, 1982). Thus, the microstructure of hypereutectoid Damascus steel is optimum for ductility.

Given the variety of crucible steel, some with a high cementite content and others with a high ferrite content, in addition to the variety of forging methods, the range of microstructures, and the presence of phosphorous and other minor or trace elements, it is not surprising that there is no consensus of opinion. The presence of small amounts of phosphorus would have affected the forging and performance of the blade, particularly the elasticity. The effects of less than 1% P in the steel would have greatly influenced the performance of the blade (Table 33). It appears that there were different types of crucible steel available, such as those that were made of hypoeutectic or hypereutectic steel, with or without a pattern and that each possessed different qualities because of their microstructure, the presence of minor and trace elements, and their subsequent heat treatments.

Table 33: The effects of phosphorus on tensile test, bend, and impact fracture properties

Phosphorus, %	Yield strength, psi	Tensile strength, psi	Elongation, %	Repeated reverse bends, number	Impact fracture toughness, ft-lb
0.06	24,800	42,000	30	96	43.5
0.10	26,000	43,900	22.5	82	31
0.19	44,600	56,100	30	67	36.5
0.29	40,000	47,700	30	61	4
0.49	69,200	77,000	21	40	1
0.76	73,100	83,200	20	11	1
1.07	72,400	85,500	15	10	1

Other elements: 0.015% C, 0.055% Mn, 0.045% Si, 0.03% S
Annealed 720°C—8 hours after hot forging and hot rolling
Reversed 90° bends over 0.26 in. radius
Charpy impact test—probably larger notch radius than present convention
[a]Loria and Krause 1936: 12

(From Rostoker and Bronson, 1990, 23)

Not only would phosphorus have made the ingot "hot short" (see above), it would have made the finished product "cold short" (brittle when cold) and this property was noticed in the past. In fourteenth century Moorish Spain, Aly ben 'Abderrahman Ibn Hodeil observed that "... the Hindy sabre often breaks when the weather is cold and shows itself better when the weather is warm" (Bronson, 1986 from Mercier, 1924, 231). This is probably due to the presence of phosphorus in the steel. Hindi sabres derived from Sri Lanka (see above), and indeed Wayman and Juleff (1999, 36) identified steadite, the iron-phosphorous compound, in a crucible ingot from there, suggesting that blades produced in Sri Lanka contained phosphorus. Blades that contain phosphorus in percentages over *c.* 0.3% can be "cold short" and those that work well and be malleable in the summer can shatter during a cold spell (Rostoker and Bronson, 1990, 22; Percy, 1864, 64).

In addition to being decorative, the Damascus pattern was a hallmark of a potentially very high quality blade. Crucible steel blades that did not have a pattern could have been just as good quality as those with a pattern, yet, those with a pattern may not have been as good as some without. However, it may not have been possible to distinguish crucible steel blades without a pattern to blades made from non-crucible steel. While blades made of other types of steel could have been equally as sharp and strong, they would not have remained as ductile because they did not have the microstructure of spheroidal cementite in a ferrite/pearlite matrix. Ductility would have been a highly important feature, particularly in long hand-to-hand combat, because a bent or shattered blade could cost the user his life. A man would purchase the best quality blade available, for himself or possibly his son who had come of age, because not only was the blade a symbol of masculinity and prestige, but it would be his defence in a confrontation, hence his reputation, status, and life depended on the chosen blade. By using the above-mentioned tests and by observing the type of pattern, a blade would be chosen. The name of a particular type of decorative pattern was often associated with a specific location, workshop or smith, who would have had a reputation for making blades of a specific quality. The long-standing reputation of crucible steel and Damascus steel blades as the best blades available appears well deserved.

Chapter 4: Investigation of Steel Objects

"...Forget that blind ambition, and
learn to trust your intuition..."
(Buffett, 1978)

Studies of archaeological objects made of crucible steel are rare compared to studies of steel made by carburized bloomery iron. Most of the latter studies have been performed on ferrous objects from numerous locations including Europe (e.g. Tylecote and Gilmour, 1986), Northern Russia (e.g. Terekhova, *et al*, 1997) and China (e.g. Wagner, 1993). The few archaeometallurgical studies that have uncovered crucible steel objects are from various time periods and locations (see below). A number of studies have also concentrated on the examination of historical Damascus steel blades (see Chapter 3). For this thesis, blades from three regions of Central Asia were examined to begin to correct this imbalance in archaeometallurgical research and to help determine the metallurgical characteristics of archaeological crucible steel.

Blades were chosen because there are Islamic textual accounts, historical and archaeological evidence that indicate swords and sabres were sometimes made of crucible steel (see Chapters 3 and below). Ideally, excavated steel objects from the same period and close proximity to the crucible steel production workshops in Turkmenistan and Uzbekistan would be examined. Unfortunately these were not available for metallurgical study. Swords, sabres, and knives from two regions of the Russian Caucasus and from one region around the Aral Sea, however, were available for laboratory analysis. A total of fifty-seven blades were sampled. Metallographic examination concluded that four of these were made of crucible steel. The others blades were either made of bloomery iron, steel from carburized bloomery iron, a combination of bloomery iron and steel, or were too corroded to confidently determine what type of iron or steel was used to produce the blade.

Various Methods of Producing Steel

It is generally assumed that the role of carbon in steel was only understood during the 18th century (Smith, 1981, 33). It is thought that many of the craftsmen were aware that certain actions would create a better product but they did not understand, by modern definition, that it was the carbon and the manipulation of the microstructure during heat treatments that caused the different properties. In Europe, since at least Aristotle's time, the differences between iron and steel were noted. Homer describes the quenching of iron (Smith, 1981, 97). Therefore, heat treatments were known relatively early in the Iron Age at least in some areas. In Europe it is only in the 1540's when we get satisfactory descriptions of steel making by Biringuccio (Smith, 1981, 34). A good description of the development of the understanding of iron production in Europe can be found in various works by Smith (e.g. 1981).

Divers methods were used in the past to produce steel. Depending upon the design of the furnace and the furnace charge, steel can be directly smelted from the ore. Smelting furnaces which allowed steel to be produced directly from the ore, on a somewhat reoccurring or intermittent basis were pre-Roman Celtic pit hearths (Pleiner, 1980, 397-398), Tatara furnaces of Japan (Rostoker *et al.*, 1989, 11-25), some East African furnaces (Rostoker and Bronson, 1990, 137), Turkic furnaces of the Altai Region (Ziniakov, 1988) and the wind-powered furnaces of Sri Lanka (Juleff, 1996; 1998).

The atmosphere inside the furnace needs to be reducing in order to smelt the ore to produce metallic iron. The reduction/oxidation (redox) atmosphere inside the furnace is influenced by the ratio of fuel to air, type of ore, temperature inside the furnace, type of bellows used, the form of charcoal, in addition to the shape and design of the furnace (Rostoker and Bronson, 1990, 25-39). For steel to be produced, the conditions inside the furnace need to be more reducing than is needed to smelt softer, ferritic bloomery iron. Trapped charcoal or high carbon iron trapped in slag can produce blooms with steely areas (Rostoker and Bronson, 1990, 135).

Most often steel was produced by carburizing bloomery iron once it was removed from the smelting furnace. There are various ways to carburize bloomery iron. During smithing, the bloomery iron is embedded in charcoal and could absorb a small amount of carbon to produce low carbon steel that remains in the metal during forging. Or the craftsmen may imbed the iron in charcoal at a temperature of 900-1100 ^{O}C for at least 5 hours to get a carburized surface 2 mm deep up to 0.45% C (Tylecote and Gilmore, 1986, 15). The charcoal carburizes the surface of the iron and produces a surface of steel. The depth of carburization and the resulting carbon percentage are dependent upon the redox conditions and temperature of the smithing hearth, in addition to the length of time the iron is embedded in the charcoal (Rostoker and Bronson, 1990, 122-123). The subsequent smithing will also affect the final carbon content of the steel.

Steel was also produced by a similar process which involved first applying a carbonaceous material such as charcoal, leaves or fat, to the surface of the iron object, then covering the object with an outer coating of a refractory, airtight material such as clay (Rostoker and Bronson, 1990, 123). The object with the coatings was heated and the carbonaceous material carburized the iron, thus producing steel.

A different process for directly smelting steel involved initially producing cast (pig) iron in the furnace that was then decarburized while still inside the furnace (Rostoker and Bronson, 1990, 136). Alternatively, steel was made by decarburizing cast (pig) iron after it was removed from the smelting furnace. Decarburization was used in China from the first century BC (see Wagner, 1993, 290). Similar techniques were also used in Japan and East Asia (Rostoker and Bronson, 1990, 149). Cast iron was also decarburized in the solid state. This method dates back to at least the Han period in the second and first centuries BC in China (Rostoker and Bronson, 1990, 149). Related processes, fining and puddling, were used to produce wrought iron in Europe only from the 15th-16th and 18th centuries onwards (Rostoker and Bronson, 1990, 139; Rostoker and Dvorak, 1990, 153). These processes produced steel by an indirect method and allowed the metal to be produced more efficiently on a large industrial scale, and eventually led to steel playing a major role in the Industrial Revolution.

Placing bloomery iron into a bath of cast iron also produced steel. Biringuccio described this method in the 16th century in Italy (Rostoker and Bronson, 1990. 126). A similar process, termed co-fusion by Needham, seems to have been used in China (1958, 5-6). Al-Beruni (Said, 1989) also described a similar method of mixing soft and hard iron, apparently to produce crucible steel (see Chapter 3).

Distinguishing Between Other Steels and Crucible Steels

Discriminating between objects made from crucible steel and those made of other types of steel is essential but can be difficult. It is necessary to identify features characteristic of crucible steel objects that are not commonly found in other steel objects. The type of steel can also imply the manner of forging required, the cost of the process in resources, and the quality of the finished item.

The most evident characteristic of crucible steel is that the steel was fully liquid during the process. This usually resulted in relatively homogenous steel with no slag, or virtually no slag trapped in the metal. During the initial stage of the solidification dendrites form, and impurities and trace elements settle in either the dendritic or interdendritic regions (see Damascus steel chapter 3). Steel made from decarburized cast iron can also be liquid; therefore, distinguishing crucible steel from other types of steel that was once liquid is problematic.

Rostoker and Dvorak (1990), Piaskowski (1992), and Starley (1999) have discussed methods of distinguishing between different types of wrought iron, and directly and indirectly smelted iron and steel. One drawback is that the investigations primarily used historical rather than archaeological data. Distinguishing between archaeological steels made by different methods, particularly from eastern regions, such as Central Asia, China and India, would benefit from additional research.

Rostoker and Dvorak (1990) studied the elemental composition of bloomery, puddling, and finery slags to determine what figures of the slag's elemental composition was statistically out of the range of the other two types of slags. From published literature and from their own samples, they considered over a hundred analyses of bloomery slag, approximately nineteen analyses of puddled slag, and one dozen samples of finery slag (Rostoker and Dvorak, 1990, 160-161). Piaskowsky (1992) added to this study by suggesting that the concentration and structure of slag inclusion, in addition to the silicon and manganese contents of the iron, could also be used as distinguishing criterion. He concluded that directly and indirectly smelted iron and steel could be distinguished by two factors. The first is the concentration and the structure of slag inclusions: there is a higher percentage of slag in directly smelted iron and steel and the slag is generally larger in size. Secondly, in indirectly smelted iron and steel, "the concentration of silicon may be 0.05 to 0.5 weight percent and that of manganese 0.05 to 2.0 weight percent" in the metal (Piaskowsky, 1992, 172). In directly smelted steel silicon and manganese occur only as trace concentrations, usually as oxides in slag inclusions.

The puddling process involves decarburization by adding oxygen to the cast iron. During the puddling process, the cast iron is liquid but freezes as the decarburization proceeds and the melting temperature of the metal increases. During solidification dendrites form. Puddled iron, however, often contain small amounts of slag. Rostoker and Dvorak (1990, 160) suggest that chemical compositions of the majority of puddling slags do not exceed 24% silica, 90% iron oxide, 3.5% alumina, 5% lime, 8% P_2O_5 and 1% alkali. They conclude that it is primarily the low potash content of puddling slags that readily distinguishes them from bloomery or finery iron slags (Rostoker and Dvorak, 1990, 163). The finished object made of puddled iron or steel might exhibit dendrites but a high percentage of iron oxides in any slag would eliminate the object from being made of crucible steel unless the slag was in an unreacted area or crucible charge.

Although finery wrought iron was liquid during the decarburization process, finery wrought iron often contains slag (Rostoker and Bronson, 1990, 142). Rostoker and Dvorak (1990, 161) note that the few analyses performed on finery slags allow only the finery slag to be distinguished from puddling slags but not always from bloomery slags. At the present time there is no evidence suggesting that finery iron was used in the production of crucible steel or Damascus steel. However, finery iron was produced in Europe from the fifteenth to the nineteenth century (Rostoker and Bronson, 1990, 139), which corresponds to the last few centuries of crucible steel production in Persia and India. Finery wrought iron could have been used in the crucible steel charge. Puddled and finery wrought iron typically contain more phosphorus and sulphur than bloomery wrought iron (Rostoker and Bronson, 1990, 144). If these wrought irons were used in the crucible charge they could add these two, and possibly other elements, to the final steel product and could affect the crucible steel's behaviour, such as possibly causing the steel to be "hot short". Manganese sulphide inclusions have been found in later crucible steel objects (Allan and Gilmour, 2000, 478), perhaps suggesting that the crucible steel was made from finery wrought iron.

In most circumstances, steel made from either a steely bloom or carburizing bloomery iron is comparatively easy to identify. Slag inclusions are indicative of bloomery iron and are often observed in the microstructure. The percentage of slag in bloomery wrought iron can range from 5-10 % (Rostoker and Dvorak, 1990, 153). Piaskowsky (1992, 172) stated the percentage of slag in directly smelted iron and steel to be about 0.7 to 3.5% volume percent or higher. Rostoker and Dvorak (1990, 161) suggested that the elemental composition of the majority of bloomery slags does not exceed 48% silica, 70% combined FeO and Fe_2O_3, 12 % alumina, 7 % lime, 8% P_2O_5 and 4.6 % K_2O. Unaltered bloomery slag would not be expected in crucible steel objects because the temperature and redox conditions associated with the crucible steel process would have altered the slag (see below).

Distinguishing between Japanese Tatara furnaces directly smelted steel and crucible steel can pose problems. The Japanese *hama-hagana* (jade steel) is a very pure hypereutectoid steel (Rostoker *et al.*, 1989, 16). This steel can be almost slag free, have a relatively homogenous high carbon content, shrinkage cavities and segregation of elements. Each of these characteristics can also be found in crucible steel. The examination of small samples might lead to misidentification of either steel due to the limited size of a sample or presumptions based on the geographic location of the find.

A sample of a high carbon area of a Tatara bloom was examined by Rostoker *et al.* (1989, 20) who found it exhibited very large grains of prior austenite with proeutectoid carbide and coarse pearlite. Rostoker *et al.'s* (1989, 23) metallographic examination and elemental analysis revealed segregation zones in the areas where the cast iron solidified. Although the carbon content could be homogenous throughout a given sample, the sample would not exhibit a dendritic structure, except in local areas where the liquid cast iron was decarburized and solidified. The lower carbon iron absorbs carbon from liquid cast iron, which sits at the bottom of the furnace. The cast iron infiltrates the bloom by capillary absorption, carburizing the lower carbon areas by liquid to solid-state carburization, and "...the liquid iron not only contributes carbon to the surrounding metal but loses carbon itself" (Rostoker *et al.*, 1989, 18-19). This segregation implies the formation of dendrites, however, the identification of dendrites in restricted areas, as opposed to across the entire sample, would signify the use of Tatara steel rather than crucible steel.

The main elements that segregated during solidification are phosphorus and sulphur. These elements in the Tatara steel form sulphides containing iron, titanium and manganese (Rostoker *et al.*, 1989, 21). Rostoker *et al.* (1989, 19) identified steadite (the iron-iron phosphide eutectic) in the Tatara steel. According to Rostoker *et al.* (1989, 19) steadite is rare in both ancient and modern steels. However, Wayman and Juleff (1999, 36) identified steadite in blooms apparently used for crucible charge and in the crucible ingot from Sri Lanka, and it was found in the ingot from Merv.

Another likely distinguishing characteristic may be found in any associated slag. Tatara slags can contain FeO contents less than 6% (Rostoker *et al.*, 1989, 15), which is higher than any crucible steel slags analysed to date, but only higher by around 2% (see below). The presence of titanium oxide would point towards Tatara steel because titanium oxide is found in many Tatara slags but is rare in other slags (Rostoker *et al.*, 1989, 15). The presence of titanium, however, is not a result of the process but the ore; therefore, titanium can also be present in slag from other smelting processes.

As mentioned above, the most evident feature of crucible steel is that the steel was liquid. Dendrites form during the cooling of liquid steel. According to Samuels (1980, 180-188) the main characteristics of industrial cast steels are dendritic coring and segregation of impurity elements. The dendritic phenomenon has also been noted in crucible steel ingots from India (Wayman and Juleff, 1999), and is a necessary factor for the formation of the pattern on higher carbon Damascus steel blades (Verhoeven, 2000, and Chapter 3). The dendrites and the interdendritic zone have different elemental compositions, primarily in regard of the carbon content of the steel but also due to the segregation of trace and impurity elements (see the formation of the Damascus pattern Chapter 3). These dendritic features remain present in the ingot and to some extent in the final object after forging. Forging, however, will affect the dendrites appearance, flattening them perpendicular to the direction of the applied force.

The liquid steel also allows slag to separate out of the metal and rise to the surface. The absence of slag in an artifact, however, does not confirm the use of crucible steel. Steel made from high quality furnace iron may have few slag inclusions and the small samples usually taken for archaeometallurgical study may not contain slag. An example of this type of steel may have been found in England from an 8^{th}- 9^{th} century, Anglo-Saxon context (Mack *et al.*, 2000; and see below). The absence of slag does not necessarily indicate the object was made of crucible steel. The presence of slag, however, does not rule out crucible steel either. If the steel were not wholly liquid, or liquid for a long enough period of time for complete separation to occur, slag would still remain in the steel.

It is presumed here that any slag found inside a crucible steel ingot or blade would be the same as, or very similar to, the slag which is found floating on the top of the ingot during the crucible steel process (see Chapter 1). This assumes that the process was successful and the slag is not imbedded in iron from any unreacted crucible charge material.

The average compositions of the Merv and Akhsiket slags were compared to Rostoker and Dvorak's (1990) limits for the elemental compositions of wrought iron slags made by different methods (see above and below). Based on the normalized analyses of the crucible slag presented in Chapter 1, excluding the three odd slags, the crucible slag from Merv does not exceed 57% SiO_2, 2.4% FeO, 20% Al_2O_3, 22% CaO, 0.2% P_2O_5, 6% K_2O. The slag from Akhsiket does not exceed 61% SiO_2, 3.8% FeO, 11% Al_2O_3, 7% CaO, no P_2O_5 was detected, 1% K_2O.

The most distinguishing feature between these crucible slags and the bloomery and puddled wrought iron slags is the iron oxide content, which has an upper limit of 70% for bloomery wrought iron slag and 90% for puddling slag, but below 4% for the crucible steel slag. Although Rostoker and Dvorak (1990, 162) did not set an upper limit for finery iron slag, their published samples have combined FeO and Fe_2O_3 percentages at least over 55%, far above that of crucible steel.

Slag has been identified in two crucible steel artifacts: the Piaskowski blade (Piaskowski, 1978, 6; and see chapter 3), and in a Turkish helmet (see below). The slag in the Turkish helmet is more akin to wrought iron because it has a reported iron oxide content of two analyses around 97% and 57% (Williams, 1997, 381). Williams suggests that the slag is the remains of bloomery iron that may not have been completely melted. Slag has also been found in the sword examined by Piaskowski (1978, 6) but its elemental composition was not determined.

Slag is not the only type of non-metallic inclusion that can occur in steels. A common feature of industrial cast steels are manganese sulphide inclusions (see Samuels, 1980, 113 and 181). Gilmour suggests that the identification of a crucible origin for steel "will probably depend on the detection of characteristic non-metallic impurities such as manganese sulphides" (Allan and Gilmour, 2000, 478). Manganese and sulphur can be found in bloomery iron/steel too, however, due to the comparatively low temperatures used in the production of bloomery iron, their presence is comparatively rare and the manganese ends up in the slag (Rostoker and Bronson, 1990, 19). According to Gilmour "...the absence of manganese sulphide inclusions is a good guide to a bloomery origin for a steel" (Allan and Gilmour, 2000, 478). While this may be true for bloomery iron, the presence of manganese and sulphur in crucible steel is only a feature of the crucible charge. If the charge contains bloomery iron, which has virtually no sulphur and manganese, even if manganese is added to the crucible, they may not be deposited as non-metallic inclusions. The crucible steel examined by Gilmour (Allan and Gilmour, 2000, 475-511) may have contained manganese sulphide inclusions, but the crucible steel was from a much later date, apart from the Nishapur sword (see below), the objects were post 17^{th} century, a date after indirect smelting processes were being used (see above). Iron from the indirect processes typically contains more sulphur, resulting from coal used to originally smelt to pig iron. If iron from an indirect method was used in the crucible charge, then the steel product could contain a higher amount of sulphur, and possibly sulphide inclusions, than crucible steel made centuries earlier. However, the deliberate addition of pyrite into some crucible charges (see Chapter 2) could complicate matters since pyrite, by definition, contains sulphur.

Another common feature of crucible steel is globular/spherical cementite. Although the appearance of spheroidal cementite is a necessary feature of the Damascus steel pattern, it is not necessarily a characteristic of crucible steel. According to Samuels (1980, 225) spheroidal cementite can be obtained in three ways:

1) Low carbon steels can be cold worked and annealed at subcritical temperatures (Samuels, 1980, 63-64). This produces spheroidal cementite in a ferrite matrix.
2) Martensite can be tempered at subcritical temperatures (Samuels, 1980, 418).
3) Cementite plates in pearlite and proeutectoid cementite can be heat treated at subcritical temperatures (Samuels, 1980, 225-229).

The key feature for producing spheroidal cementite is that the final stage of heating is at a subcritical temperature, that is, just below the austenite transformation temperature, (A_1 is the eutectoid line, around 727^{O}C), and it can be produced in any type of steel or cast iron that contains cementite. Therefore, spheroidal cementite is only a feature of the final heat treatment and not a necessary characteristic of crucible steel, although it is often observed in crucible steel objects and is a feature of the pattern of hypereutectic Damascus steel blades. Indeed, spheroidal cementite has been recorded in a short sword from a pre-Han (before 206 BC) grave in China (Wagner, 1993, 281) and also noted in a number of Roman and post Roman knives from Britain (Tylecote and Gilmour, 1986, 33-36).

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The earliest crucible steel blade is dated to the 1st century AD and was reported by Hadfield as composed of high carbon steel with spheroidal cementite (Marshall, 1951, 536). This sword was not complete but was double edged and said by Marshall to be of the same type found on the stone statue at Mathura of King Kanishka, a Kushan king (Marshall, 1951, 545). It was during the first century that the Persians ruled Taxila (Dani, 1986,66-71). The second two crucible steel objects are a sword and an adze dated to the 5th century AD, when the White Huns ruled Taxila (Dani, 1986, 75). Hadfield reported that two swords and adze were made of high carbon steel with virtually no non-metallic inclusions or slag (Marshall, 1951, 536), thus likely to be crucible steel. Hadfield (1951, 536) and Biswas (1996, 277) seemed surprised that the two swords and the adze did not show signs of tempering because Indians apparently produced quenched martensite since the 3rd century BC (Biswas, 1996, 277). This, however, is not so surprising when one considers that many examples of crucible steel objects do not show extensive signs of quenching and tempering (see below).

So-called "torpedo shaped ingots" were also found at Taxila from a first century AD context. These were analysed by Biswas (1996, 276-277). Their microstructure is reported as porous wrought iron and Biswas (1996, 277) believes that they were ingots to be used in the crucible steel process. This however is unsubstantiated and they could have been used as projectiles for a slingshot or similar instrument. If they were raw materials for crucible steel, they would probably have been found in association with a metallurgical workshop. Their use, therefore, is still uncertain.

The next published object made from crucible steel is a Sasanian sword attributed to the 6th or 7th century Iran, now housed in the British Museum (Lang *et al.* 1998; Craddock, 1998, 48). As the sword was not found during a controlled excavation it has no related archaeological context, it is assumed to be dated by its stylistic attributes. It is a double-edged sword with a pistol grip and an indentation in the hilt for an index finger, but no guard. It is associated with a scabbard with two-point suspension. Under low magnification (x100) the sample shows a mottled structure after etching in nital. This phenomenon was also noted in other crucible steel objects. The microstructure consists of globular cementite in an irresolvable/fine pearlite matrix. The fine pearlite matrix indicates that the final cooling was rapid (Lang *et al.*, 1998, 9). The cementite is not aligned and therefore the sword would not have had a Damascus pattern. The globular cementite can also be observed in the corroded areas. Rounded and very small inclusions were observed in the microstructure but it was determined that they are not slag (Lang *et al.*, 1998, 8).

A sword excavated at Nishapur in Iran and now in the Metropolitan Museum of Art, New York, is presently attributed to the late 8^{th} –9^{th} century AD (Allan and Gilmour, 2000, 54). "The Nishapur sword consists of a long, straight single-edged blade with cross guard attached; the upper part of the hilt, two gilt -bronze mounts, and a ring attached to a boss like plate were also found" (Allan, 1982, 56). The sample was highly corroded but some structures were preserved while others could be seen as remnant structures in the corrosion. Gilmour examined the microstructure and recorded cementite needles and spheroidal cementite particles (Allan and Gilmour, 2000, 55). Gilmour also notes that "the overall pattern of corrosion was aligned parallel to the mail (flat) plane of the blade, suggesting that this blade may once have had a layered structure similar to that found in later watered-steel objects, particularly swords"(Allan and Gilmour, 2000, 54). This layered pattern of corrosion, however, is often seen on corroded iron objects and is more likely the cause of the apparent layered structure.

Crucible steel objects have also been reported from the Early Middle Ages in North-East Semirechie, Kazakstan (Savelieva *et al.*, 1998) at the medieval town of Tal'har. Remains of a scissors and a chisel were excavated from a 11^{th}-14^{th} century context apparently from a blacksmiths workshop. The steel was said to be of the ledeburite class. Ledeburite is associated with hypo-eutectic white cast irons and the microstructure is composed of austenite and cementite, or austenite's low temperature structure e.g. pearlite (Hume-Rothery, 1966, 318; Samuel, 1980, 21). Whether or not these are actually made of crucible steel or cast iron, or indeed cast iron produced in a crucible is uncertain from the brief description in Savelinva *et al.'s* (1998) paper.

According to Ziniakov (pers. com.) two medieval swords made of crucible steel have been excavated in Western Siberia but these have not been published. However, meeting with Prof Ziniakov convinced me that he has extensive knowledge of crucible steel; therefore, his interpretation is probably correct. Hopefully future collaborative research can support this.

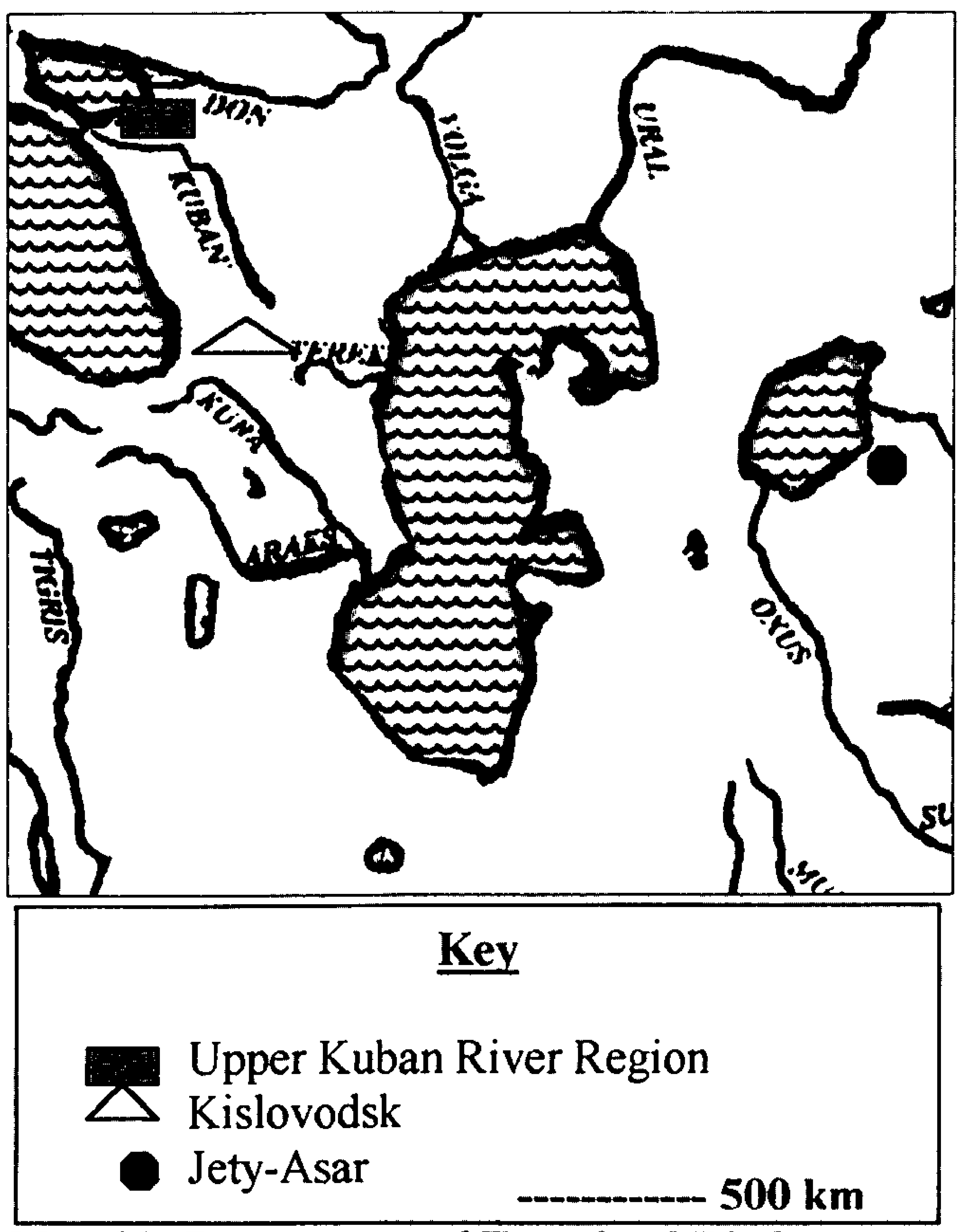
Williams (1997, 380) analysed a selection of Turkish armour including a 16th century Turkish helmet, now in the Museum of St. John, Clerkenwell (London) which he concludes to be made of " wootz". The microstructure is described as "a mass of carbides as tiny globules in a ferrite matrix" (Williams, 1997, 380). The hardness of the helmet is 342 VPH which compares closely with Piaskowski's (1997, 380) reported average of two Damascus steel swords as 348 VPH and 366 VPH. Williams also states that it is apparently an "annealed white cast iron" and "the supposition must be that it is wootz". There is no reason to assume that it was made of "wootz" imported from India, when the provenance could have been Central Asia, or perhaps even Turkey itself.

Another group of objects apparently made of steel that was once liquid are attributed to 8th- 9th century Anglo-Saxon England. These were recently examined by Mack *et al.* (2000) and have caused some controversy in archaeometallurgical circles (Arch-Met, 2001). During excavation thousands of objects related to iron processing were uncovered. The microstructure of some of the remains was very different from other known Anglo-Saxon objects (Mack *et al.*, 2000, 87). The reported distorted dendritic structure from the chisel tip appears very different from those observed in crucible steel. However, this might just be a feature of the etchant and the magnification. One of the fragments was egg shaped and was composed of cast iron and had glassy slag covering the lump. The glassy slag was reported as having 8-18% FeO, which is over 4% higher than known crucible steel slags (see above). The presence of white cast iron and eutectoid steel in crucible steel is not uncommon from either Central Asia or India (see Chapters 1 and 2). Anglo Saxon sites occasionally contain materials imported from far a field so it is not impossible that crucible steel was imported to England. However, a crucible origin is not the only possible method, direct smelting is also possible. Without further research it is only possible to state that the fragments were made of an iron-carbon alloy that was at one point liquid, at least in certain areas.

Examination of Steel Blades

Understanding the various metallurgical traditions of Central Asia is an awe inspiring task as the study encompasses such a large geographic area with many different groups of people each with their own metallurgical traditions and trading affiliates. In order to assess the extent of crucible steel use in Central Asia, the appearance of crucible steel and other types of steel needs to be determined. Few in-depth metallographic studies of iron objects in Central Asia have been undertaken. These studies include Terekhova *et al.* (1997) who have exhaustively examined iron-processing remains from as early as the 1st millennium BC from the border region of Eastern Europe and northwest Central Asia. Other studies of early ferrous objects include blades from Luristan (e.g. Moorey, 1991) and from Taxila (Hadfield, 1951; Biswas, 1996). Furthermore, in the far northeast, in the Altai Mountains, Ziniakov (1988) has studied remains of Turkic ferrous metallurgy during the sixth to tenth centuries AD. Each of these studies is important and informative, however there remain many gaps in our understanding of ferrous metallurgy in Central Asia during all time periods. To help fill these gaps, blades from the Russian Caucasus and the Aral Sea region were examined (Map 11). During the research, it was particularly hoped that crucible steel blades would be discovered because less than a dozen crucible steel objects from archaeological contexts have been published so far, and only one report provides detailed information (see below). By examining blades from various regions of Central Asia, any crucible steel blades found would allow firsthand examination that could be compared to reports of crucible steel objects, Damascus steel objects, and related textual accounts. This would further assist in ascertaining possible characteristics unique to crucible steel objects from archaeological contexts. The study would also begin to place crucible steel in the broader history of Central Asian metallurgical and related practices, such as trade and warfare.

The examined objects range from knifes, daggers and spearheads, to sabres, single-edged and double-edged swords. Eighteen bladed objects from the Kislovodsk depression and now in the Kislovodsk Museum, ranging in date from the 3rd - 12th centuries AD, were examined by metallographic analyses to assess the materials and methods used in their manufacture. These were dated by finds found along with the blades in the graves or by style. A preliminary study of early medieval weapons excavated from cemeteries in the northern Caucasus showed changes over time in the mode of warfare, associated with different local tribes and nomads (Kaminsky, 1996). In addition, nineteen blades from the Upper Kuban River region were analysed. These blades were not uncovered during controlled excavations and therefore have no associated archaeological contexts or firm date. However, Dr. Arzhantseva, curator of this collection in the Jewish University in Moscow, is currently undertaking stylistic studies and investigating the location of the graves which yielded the blades.



Map 11: Provenance of Examined Blades.

A further twenty blades from the Jety-Asar culture cemeteries from the 2^{nd} – 5^{th} centuries AD were also sectioned for metallographic analyses. The site was excavated by the Russian Academy of Science (Levena, 1996) and the blades are now stored there. The Jety-Asar culture lived in the southeastern region of the Aral Sea between the channels of the Syr Darya. The proximity to Merv, on the other side of the Kara Kum desert, and the fact that crucible steel was found in Kazakhstan in a later date (see below) justified sampling the corroded objects. Unfortunately, the extent of corrosion was too great to identify the types of iron used. Only one sample contained preserved cementite, however, whether the blade was made of crucible steel remains uncertain (see below).

The microstructures of all non-crucible steel blades are summarized below. These are illustrated and discussed in more detail in Appendices N, O, and P. Blades that were entirely corroded beyond identification are not illustrated or discussed. The crucible steel blades, their dimensions and their microstructures are discussed below. The length is given as the measurement of the entire blade from the bottom of the tang to the tip. The width refers to the size of the blade at the mid section or the best-preserved area. Thickness refers to the thickness at the top edge of sabres. The arrows indicate the location where the samples were removed. All the samples of the JUM blades (Jewish University in Moscow) were taken from the area near the handle so as to not disfigure the blade. Unfortunately, if the edge near the tip was carburised or a piece of steel was forge welded to the tip, the sample will not necessarily exhibit these features. The KIS (Kislovodsk) and RAS (Russian Academy of Science) samples were often taken from less corroded areas or where the blades would not be disfigured, thus the small sample may not always be representative of the entire blade. The samples were mounted in resin with the transverse side positioned for examination. All the samples, except those that were completely corroded, were examined after etching in 3% nital. Metallographic examination of the samples from the different regions indicate that the blades were made using a variety of materials and methods, which do not correlate significantly to either the provenance or the presumed date of manufacture or burial (Table 34). The examination of the samples indicated the use of iron, carburised iron, forge welded or piled iron and steel, and crucible steel, in the various blades.

Table 34: Summary of the Blades' Microstructures

Location	Sample Number	Microstructure	Blade Type
Kislovodsk	1	Crucible steel	Sabre
	2	Crucible steel	Double edged sword
	3	Carburised iron	Double edged sword
	4	Iron	Double edged sword
	5	Iron	Sabre
	6	Forge welded	Sabre
	7	Forge welded	Dagger
	8	Carburised iron	Sabre
	9	Forge welded	Knife
	10	Crucible steel	Double edged sword
	11	Too corroded	-----------
	12	Carburised iron	Double edged sword
	13	Carburised iron	Spearhead
	14	Iron	Double edged sword
	15	Crucible steel	Double edged sword
	16	Too corroded	----------
	17	Carburised iron	Sword fragment
	18	Piled	Knife
Jewish University in Moscow	1	Carburised iron	Sabre
	2	Forge welded	Double edged sword
	3	Carburised iron	Dagger
	4	Carburised iron	Double edged sword
	5	Iron	Sabre
	6	Carburised iron	Sabre
	7	Forge welded	Sabre
	8	Forge welded	Sabre
	9	Piled	Knife
	10	Iron	Knife
	11	Iron	Knife
	12	Iron	Knife
	13	Iron	Knife
	14	Forge welded	Knife
	15	Forge welded	Knife
	16	Iron	Knife
	17	Forge welded	Knife
	18	Carburised iron	Sabre
	19	Carburised iron	Knife
Russian Academy of Science	2	Perhaps crucible steel?	Sword
	All other samples were too corroded to positively determine their composition.		

Iron Blades

The samples taken from nine blades are composed only of iron: three from Kislovodsk (KIS #4, #5, #14) and five from Upper Kuban River region (JUM #5, #10, #11, #12, #13, and #16). The microstructures were composed of ferrite grains with varying amounts of slag inclusions. It seems likely that at least some of the blades had either a carburised steel edge or an edge of steel forge welded onto an iron core because iron is so soft that the blade would not have held its shape or an edge during use. The evidence for steel may have corroded away or is not observed because the sample is not representative of the entire blade.

The possible exception to this is blade KIS #14, which was ritually bent. Some of the ferrite grains are 0.5 mm in length, indicating a very soft blade that would be beneficial in bending the sword to such a twisted shape. It may have been deliberately made for a ritual and/or burial therefore there was not necessarily a need to give the blade a sharp edge and the presence of carbon would impede bending.

It is particularly surprising that samples of the sabres reveal iron and not steel. However, it may be that the area near the handle was made from a softer metal to provide some flexibility to the blade, but the edge of the blade may have been made of steel. Although the samples are composed of iron rather than steel, three blades have evidence of quenching, JUM # 11, # 13 and # 16. JUM #13 appears to have carbide or nitride etch pits, which according to Samuels (1980, 69) often appear in quenched ferrous objects. JUM #11 and JUM #16 have lathes inside the ferrite grains. These also may be a form of carbides or nitrides that sometimes appear as lathes in ferrite (see Tylecote and Gilmour, 1986, 5). Quenching is usually associated with steel rather than iron, as quenching has a dramatic hardening effect on steel, but virtually no effect on iron. The process involves heating steel between 700 - 850 ^{O}C and then suddenly cooling it in water or another substance such as oil. The evidence of quenching suggests that either part of the blade was composed of steel, or the smith quenched the blade but did not realize that it was not steel, or the sample did not reflect the composition of the entire blade.

Carburized Iron Blades

The metallographic examination of the samples revealed that eleven of the blades, KIS #3, #8, #12, #13, #17, and JUM #1, #3, #4, #6, #18, and #19, are composed of steel or have a steel edge made by carburising iron. This was determined by the observation that the samples had a relatively continuous increase in the amount of carbon from the core outwards, hence more iron-carbon phases towards the exterior edge of the object. The most common microstructure was intergranular pearlite/bainite/martensite between grains of ferrite (KIS #3, #12, #13, #17, JUM #4, #6, #19). The depth of carburization, the grain shape and size differs between samples indicating variations in forging techniques and the rate of cooling. One sabre (JUM #1) and the dagger (JUM #3) appear to be evenly carburized throughout the sample. This may be due to the use of a steely bloom or a longer carburizing period that increased the depth of penetration of the carburized area.

KIS #8 possesses a very different microstructure. The blade is contains tempered martensite and the tang contains areas of plate martensite. The tempered martensite would have produced a hard and sharp blade. Another blade composed of martensite is JUM #18. Small lines within the grains may be nucleation points of lath martensite (see Samuels, 1980, 329).

Layered Blades

Eleven blades were made by forge welding layers of iron and steel; KIS #6, #7, #9, #18, and JUM #2, #7, #8, #9, #14, #15, and #17. The process of forge welding involves heating the iron or steel to at least $1300^{o}C$ and hammering (forging) separate pieces together to form a single piece. At this temperature the slag in the wrought iron is molten and prevents oxidation of the surface, which would inhibit the bond. A steel layer can be welded to the cutting edge or many layers can be "piled" on each other and welded together, thus producing what is known as piled steel. The difference between forge welding and piling is the number of layers of iron and/or steel but there is no standard number, which distinguishes between them. Blades KIS #18 and JUM #9 were clearly made of piled iron/steel and the many layers are observed as alternating light and dark bands in the etched sample. JUM #8 appears to have a piled edge forge welded onto an iron layer. Forge welding was also used to decorate blades, most notably to produce pattern welded Damascus steel blades.

Forge welding is fairly easy to detect when a sample is etched. The samples of all the forge-welded blades have zones with different carbon contents appearing as lighter or darker bands representing the original individual iron or steel pieces. Elongated areas of slag inclusions, at the join between what were separate pieces, were observed in virtually all of the samples (e.g. KIS #7). Particularly noticeable in sample KIS #6 was an area that etched lighter than the other areas. This is a common feature often observed in forge-welded pieces and is often attributed to the presence of arsenic (Tylecote and Gilmour, 1986, 15). As the samples were not crucible steel, they were not investigated by EPMA, therefore the elemental composition is unknown.

Examination of Crucible Steel Blades

The difficulties of distinguishing between crucible steel that has a corroded surface or does not exhibit a Damascus pattern, from other types of steel, were discussed in Chapter 3. The conclusion was that there is not a singular characteristic that can be used to conclusively distinguish crucible steel from other types of steels. However, the appearance of characteristics including: a lack of slag inclusions, an homogenous carbon content across the sample, a mottled appearance across the sample, and spheroidal/globular cementite in a pearlitic/ferritic matrix, all point towards the use of crucible steel because these features are not commonly observed together in other types of steel. Apart from the mottling effect, all these other features are also characteristic of Damascus steel.

According to these criteria, four blades from Kislovodsk, # 1, # 2, # 10 and # 15 are made of crucible steel. A fifth blade, from Jety Asar (RAS # 2) is heavily corroded but retains features suggesting it too is made of crucible steel (see below).

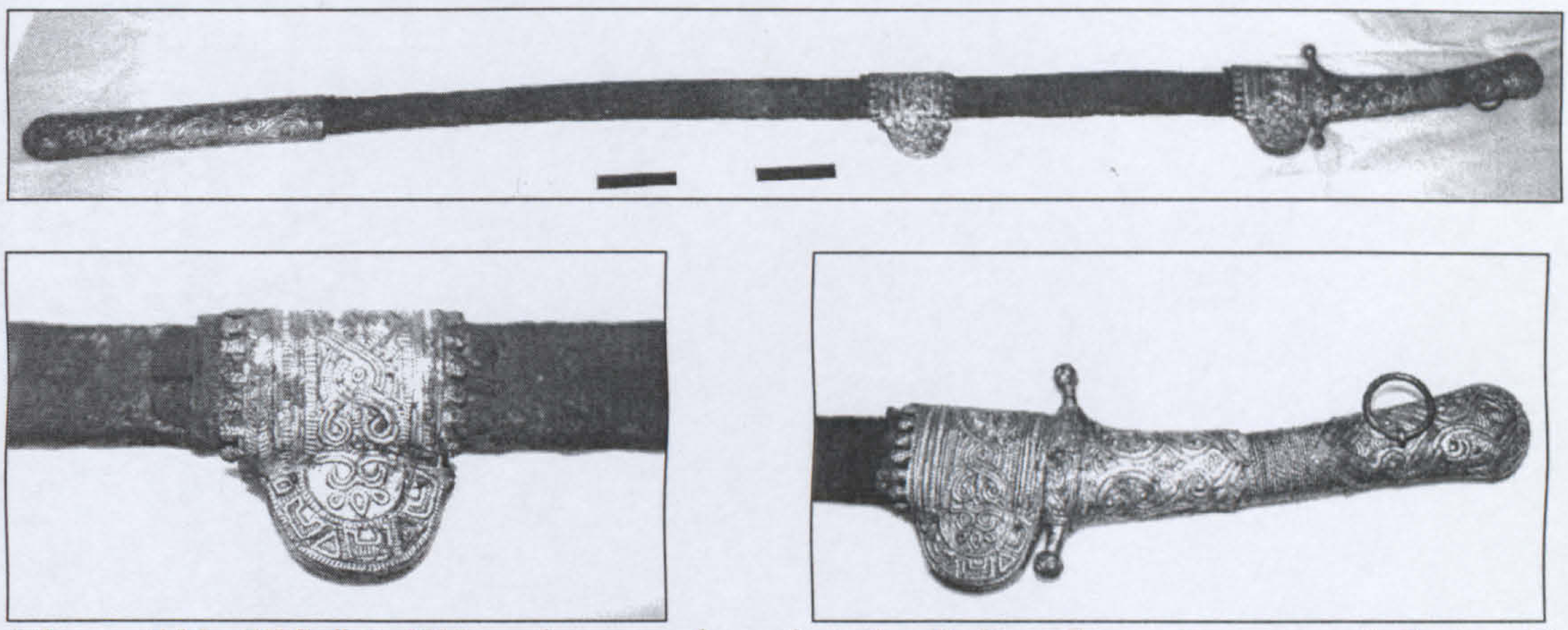


Figure 102: KIS # 1, This sabre was found at the Koltso Gora, Cemetery 1,Grave 41 and is attributed to the late 11th century AD. It measures 98 cm long, 3 cm wide and is 0.5 cm thick at the spine (scale 5 cm intervals).

The latest blade examined was a late 11th century AD sabre from Koltso Gora (Figure 102). The handle, guard, two-point suspension points and the tip guard are gold plated over a copper alloy. The gold plate is decorated using repoussè or a similar method, into intricate geometric patterns. The sabre is attributed to the Saultovo Mauaskaya culture, a culture related to the Khazar Turks, before the invasion of the Tatar-Mongols (Arzhantseva, pers. com.).

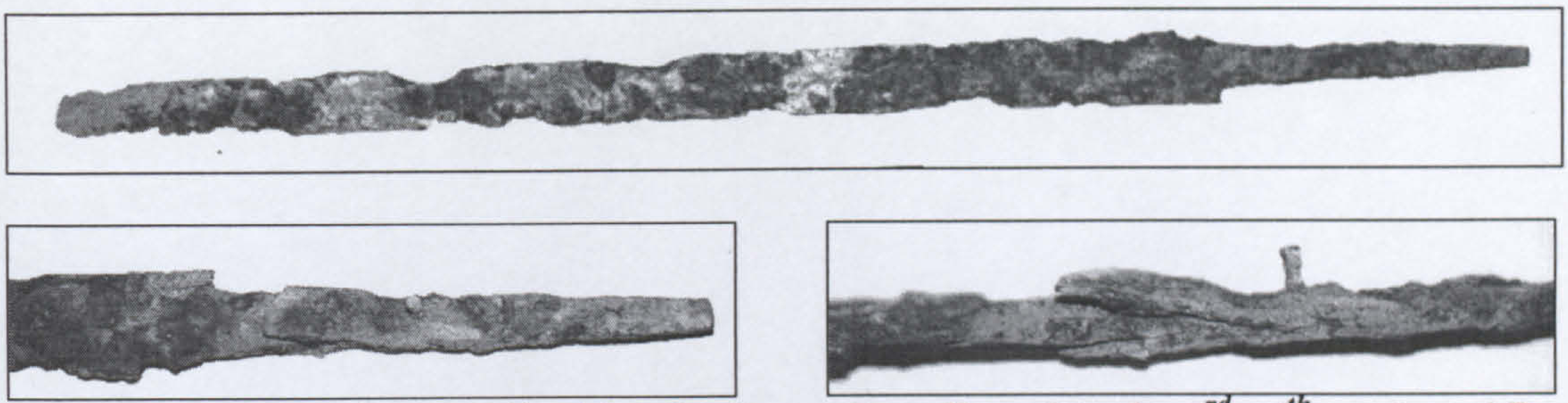


Figure 103: KIS # 2 is a double edged sword attributed to the 3rd –4th century AD from Klin Yar, Cemetery 3. It measures 82 cm in length with a width of 4 cm.

KIS # 2 was one of the earliest blades examined. It is associated with an early Alani burial at Klin Yar, dated to the 3rd – 4th century AD. The sword has a handle made of piled steel which was riveted to the blade (Figure 103).

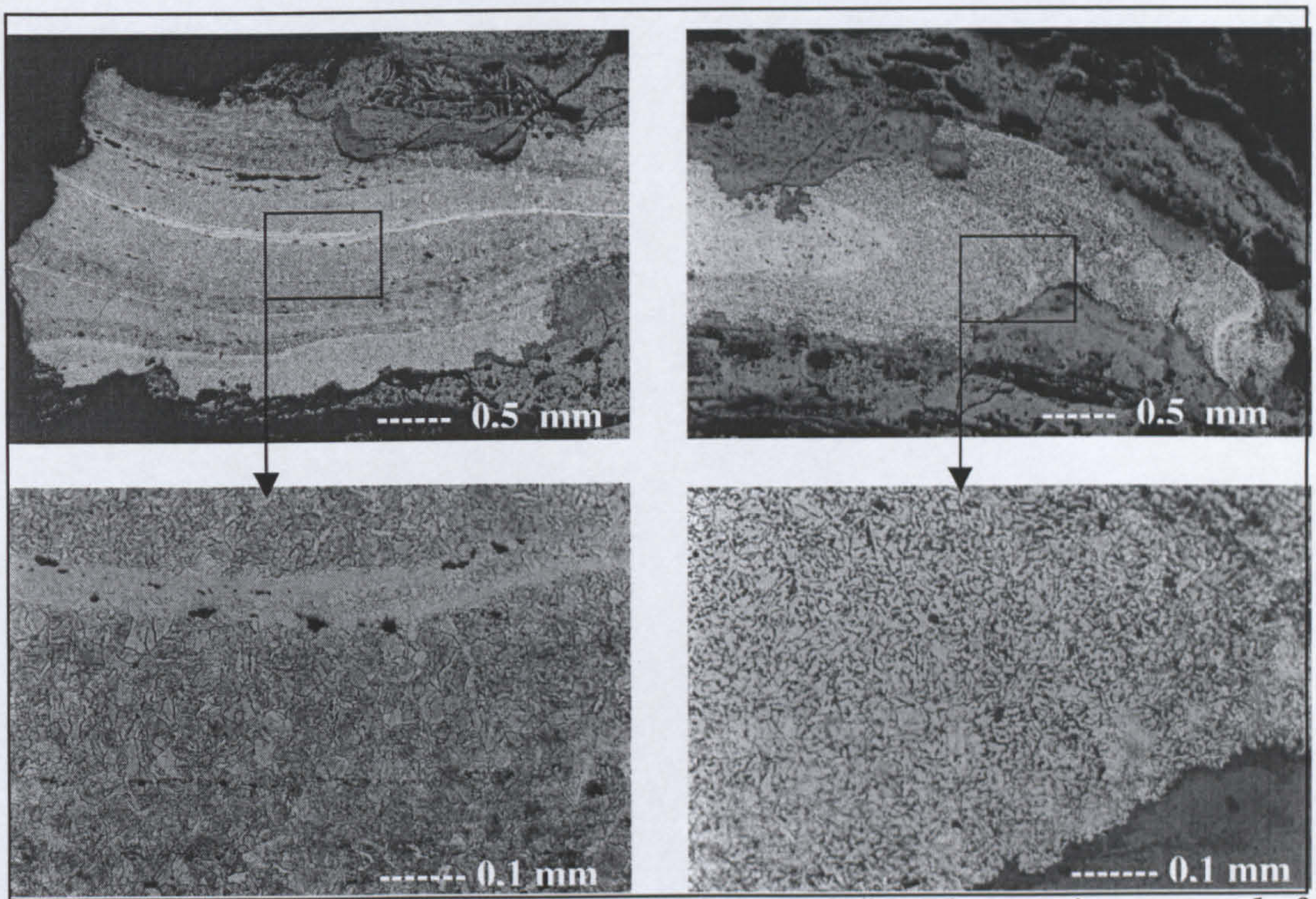


Figure 104: Photomicrographs of the tang from KIS # 2. The tang is composed of many layers of iron and steel.

KIS #10 and #15 are only pieces of blades. Both blades are attributed to the Alani culture. KIS #10 is a fragment of a presumably double-edged sword from the 7th century AD. The blade was found in a horse burial. Horse burials were a common practice among pagans for centuries across Central Asia and in Europe and are usually associated with nomadic groups.

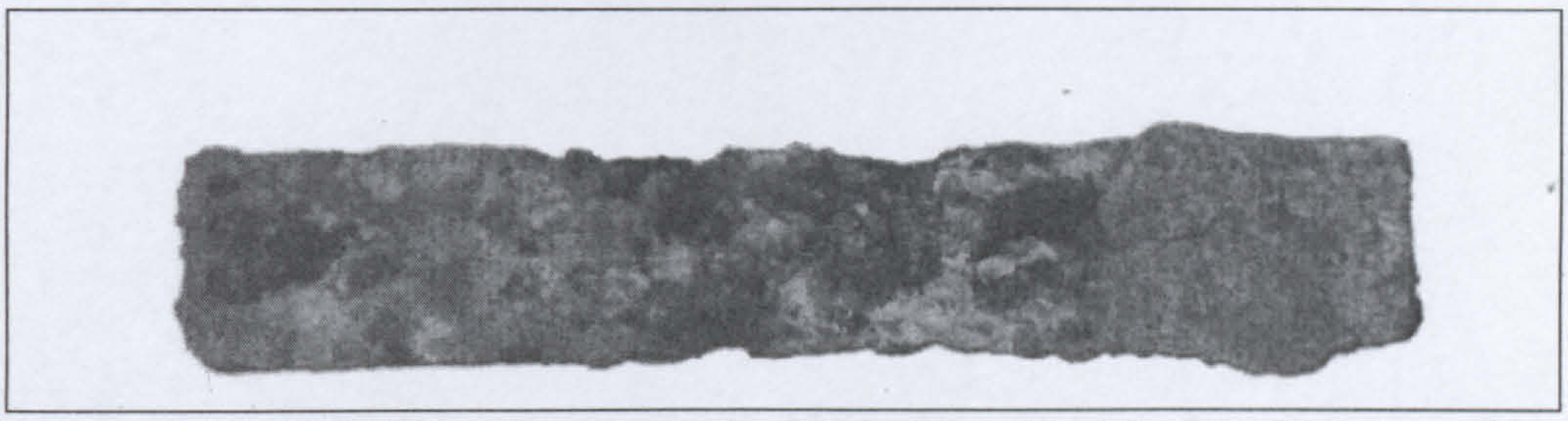


Figure 105: KIS #10, a fragment of a blade found in Machte Cemetery. The remaining length is 21 cm and the width is 4 cm.

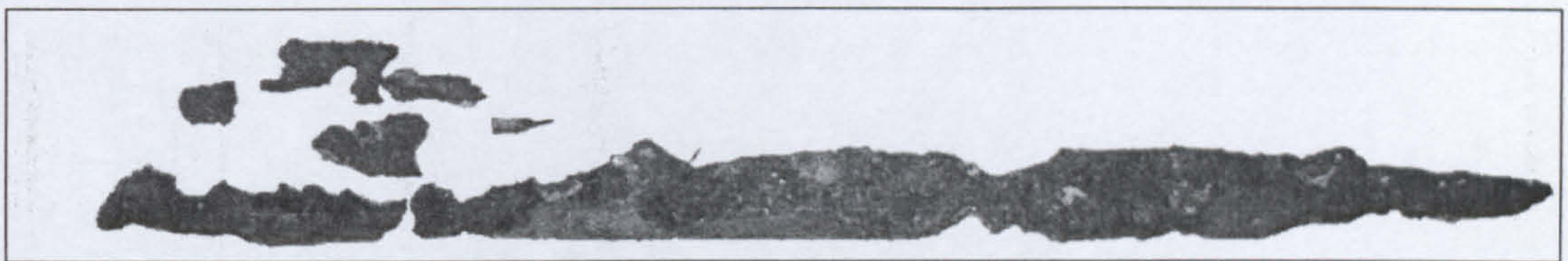


Figure 106: KIS #15, pieces of a double edged sword from 3rd –4th century Klin yar. The remains measure 76 cm in length and 5 cm in width.

Examining the four crucible steel blades under low magnification after etching in 3% nital, revealed that each exhibited a mottled pattern consisting of elongated light and dark areas in a preferred orientation parallel to the blade (Figure 107). This feature was also noted on crucible steel blades reported by Lang *et al.*, (1998), Allan and Gilmour (2000), and France-Lanord (1969).

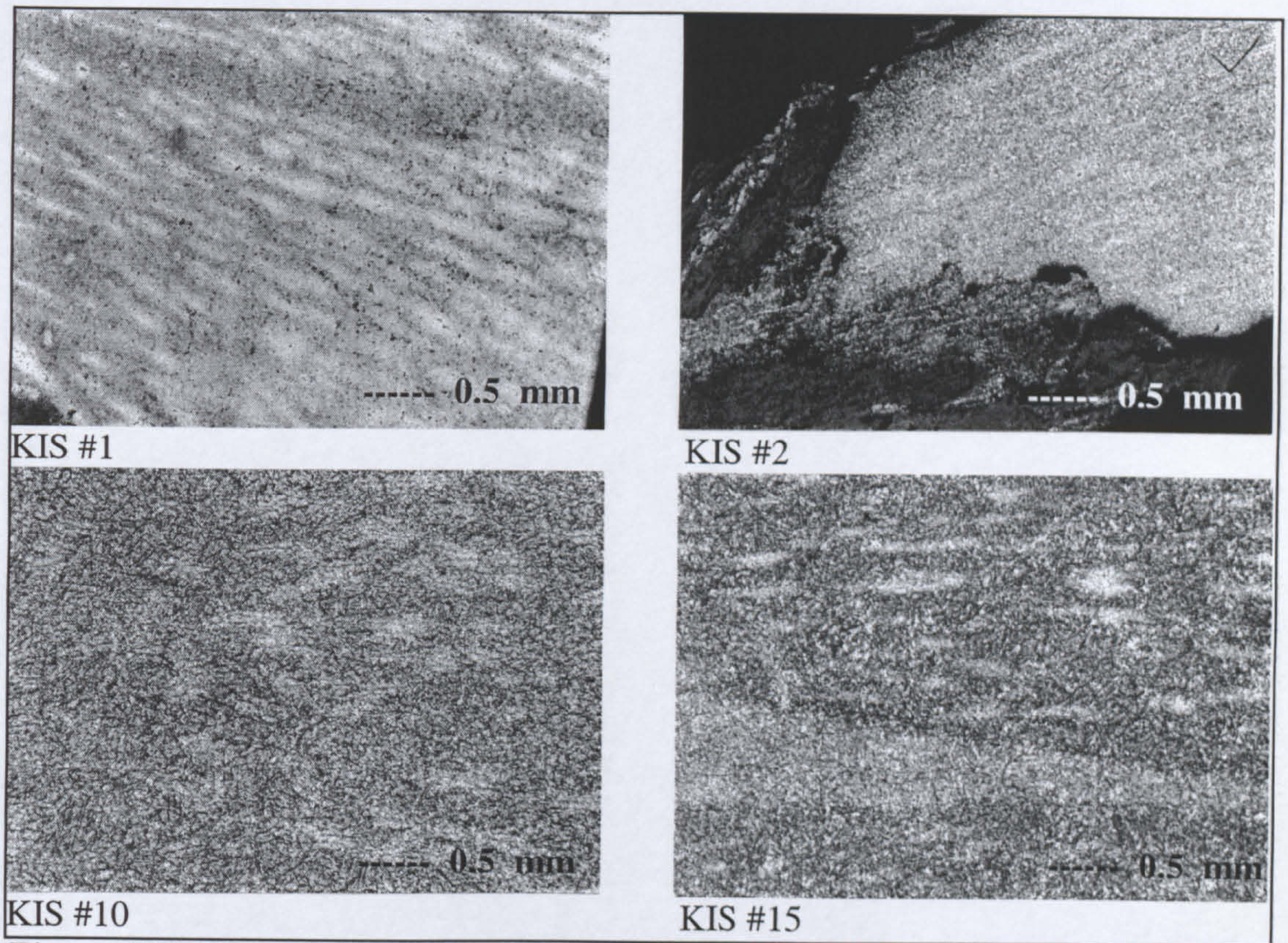


Figure 107: Photomicrographs of four crucible steel blades after etching in nital.

The clarity, size and concentration of the mottled areas differ between samples. KIS #1 has a clear pattern over the entire sample with mottled areas around 0.5 mm long and 0.05 mm wide. The mottled pattern of KIS # 2 is not as clear. The mottled areas are difficult to measure as they are so faint, but appear longer and much thinner than in the previous sample. In KIS #10 and KIS #15 the mottling appears to be more random than in the previous samples. The mottling tends to be more spherical and unevenly distributed throughout the sample. This mottling was also apparent after etching with Oberhoffers's etch (e.g. Figure 108) therefore, signifying that the effect is due to segregation of minor and trace elements that occurred during solidification.

The mottled pattern may reflect the original dendritic structure that has become flattened and elongated during forging.

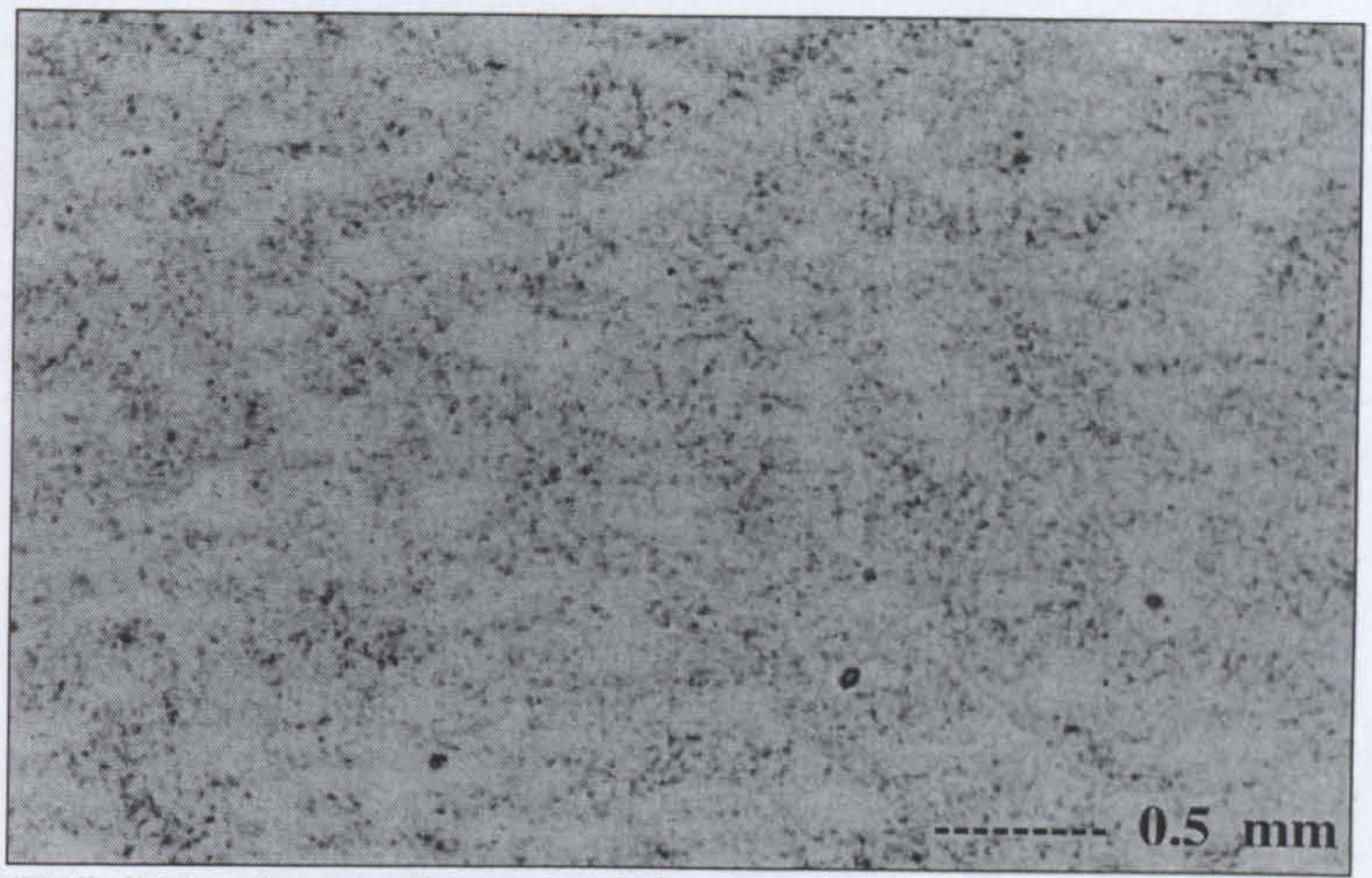


Figure 108: KIS #10 after etching in Oberhoffer's etch. Note the mottled pattern.

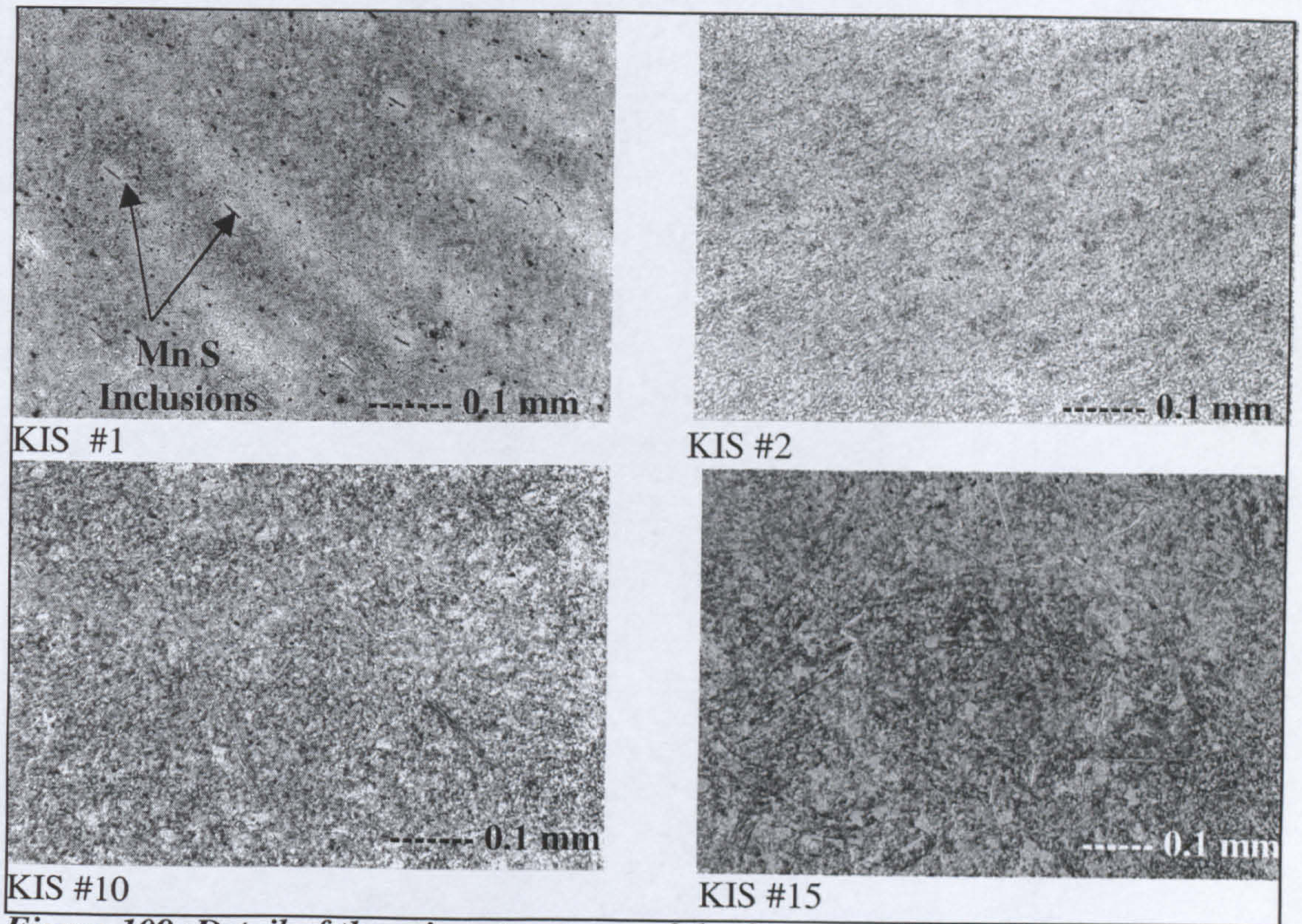


Figure 109: Detail of the microstructures of the four crucible steel blades.

Under higher magnification the differences in microstructures become more visible. KIS #1 contains elongated inclusions. These were identified as manganese sulphide inclusions by EPMA spot analyses as Mn 20%, S 19%, and Fe 40% (Appendix Q).

The high iron content may be from the surrounding matrix due to their small size. The microstructure is very fine and difficult to observe. It consists of cementite needles that are beginning to break-up and form elongated globular cementite. There is no preferred orientation of the cementite. Some of the cementite seems to be located at prior austenite grain boundaries. The matrix is composed of irresolvable pearlite. The hardness was determined to be 345 VH. The hardness and structure is comparable to a 1.5% C experimental sample made by Furrer (Harsh, 2001).

The microstructure of KIS #2 is comparable to that seen in some blades with a Damascus pattern. The microstructure is composed of globular cementite in a DET matrix (divorced eutectoid transformed matrix of cementite particles in ferrite, see Verhoeven *et al.,* 1998). The DET microstructure (Figure 109) indicates that the blade was air-cooled (Verhoeven *et al.,* 1998). The cementite has a diameter from about 1 - 5 μm. This is consistent with Verhoeven *et al.'s* (1998) finding that Damascus steel has an average cementite diameter of about 6μm. The alignment of the cementite, however, is not very strong indicating that the blade would not have had a crisp Damascus pattern (Figure 110). The microstructure is similar to Zschokke's sword # 7 (Figure 111) which has a Damascus pattern.

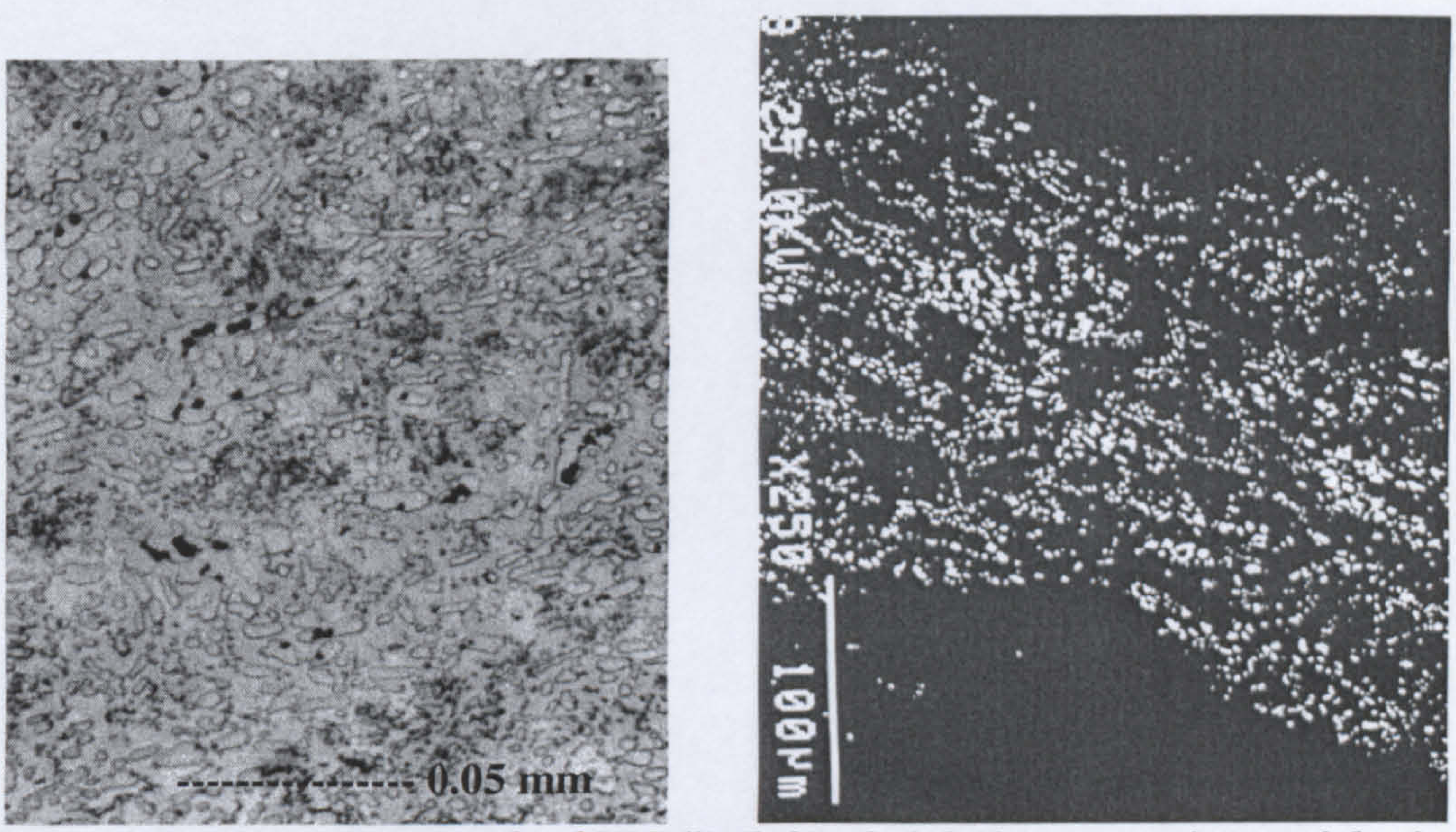


Figure 110: Photomicrograph of KIS #2 (left) of globular cementite particles in a DET matrix (cementite in ferritic matrix). The illustration on the right is a backscattered electron image of the partially corroded area of KIS #2 showing a roughly linear alignment of globular cementite in a corroded matrix.

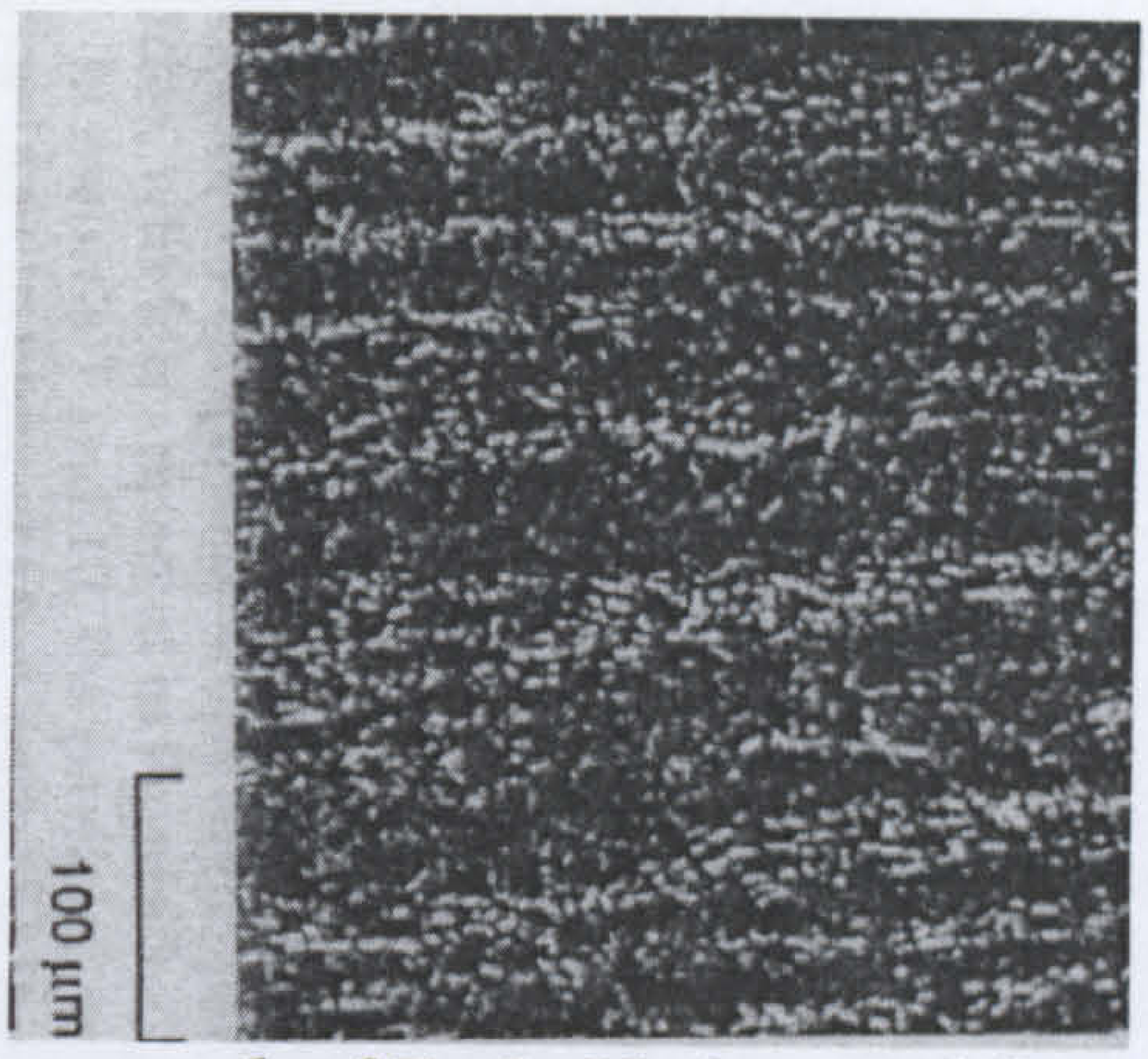


Figure 111: Photomicrograph of Zschokke's sword #7 (from Verhoeven et al., 1998). Note the similarity between this sample and KIS #2. The clearer alignment of cementite in this sword would have produced a clearer pattern than the KIS #2 blade

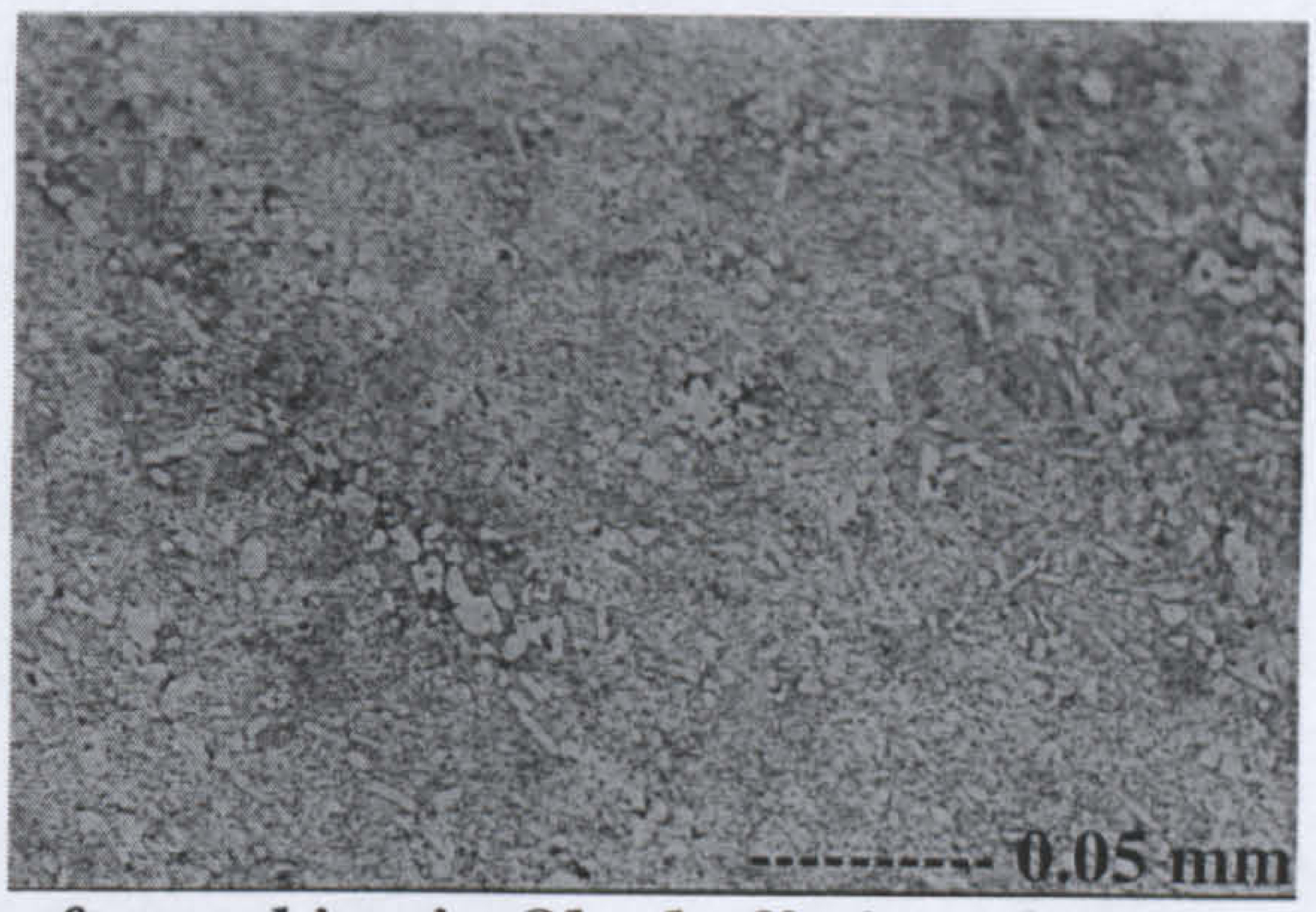
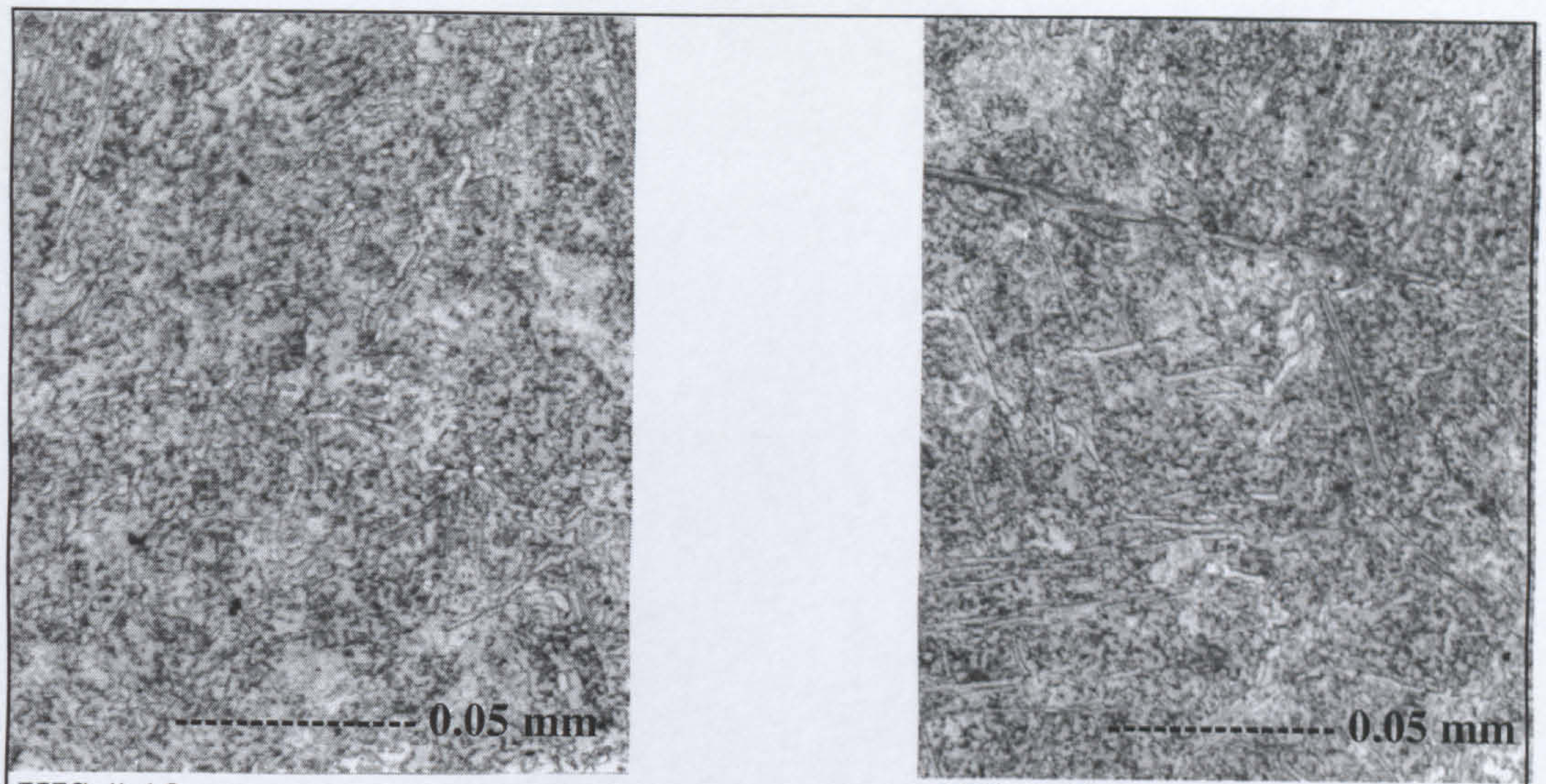


Figure 112: KIS #2 after etching in Oberhoffer's etch. Note how the areas rich in impurity elements (dark areas) also contain the aligned globular cementite.

The fragments of KIS blades #10 and #15 have a similar microstructure (Figure 113). In both blades, elongated cementite needles and prior austenite grain boundary cementite are beginning to break up and becoming more globular appearance. The matrix is composed of very fine pearlite.



KIS # 10 KIS #15

Figure 113: Detail of the microstructure of KIS #10 and KIS # 15.

The average elemental composition is presented in Table 35 and Appendix Q. Elements analysed for but not detected in high enough quantities above the noise limit to confidently state they are present include: C, P, Al, S, Ni, As, Ag, Ti, Au, V, Ba, and Cr.

Table 35: Average elemental Composition of Blades

Sample	Fe	Mn	Cu	Total
KIS #1	95	0.3	0.08	96%
KIS #2	98	ND	0.1	98%
Tang	96	ND	0.3	96%
KIS # 10	100	0.1	0.01	100%
KIS #15	99	0.02	0.01	99%

The presence of manganese in three of the blades (KIS #1, #10, and #15) is significant because it may have been deliberately added to the crucible charge. The absence of manganese in KIS #2 was unexpected because in this blade the cementite was beginning to align and manganese is one of the elements that promotes cementite banding. Other impurity elements, which promote banding such as vanadium, could be causing the cementite to begin to form bands.

One of the blades from Jety Asar (RAS # 2) may be made of crucible steel (Figure 114). The extent of the corrosion is too advanced to detect any mottled structure under low magnification. The sample is composed primarily of corrosion with elongated areas of preserved cementite (Figure 115). The cementite appears to have begun to break up into globules when the blade was being forged. The microstructure of the cementite is not unlike that found in KIS #15, both have cementite needles that are beginning to break up and form spheroids.

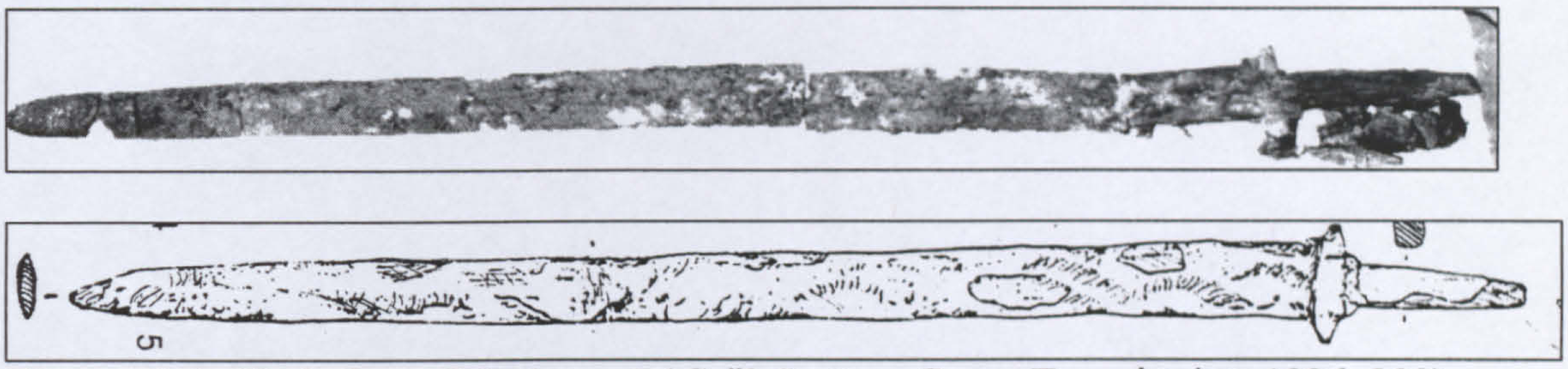


Figure 114: Blade from Jety Asar RAS #2 (bottom figure From Levina, 1996, 280)

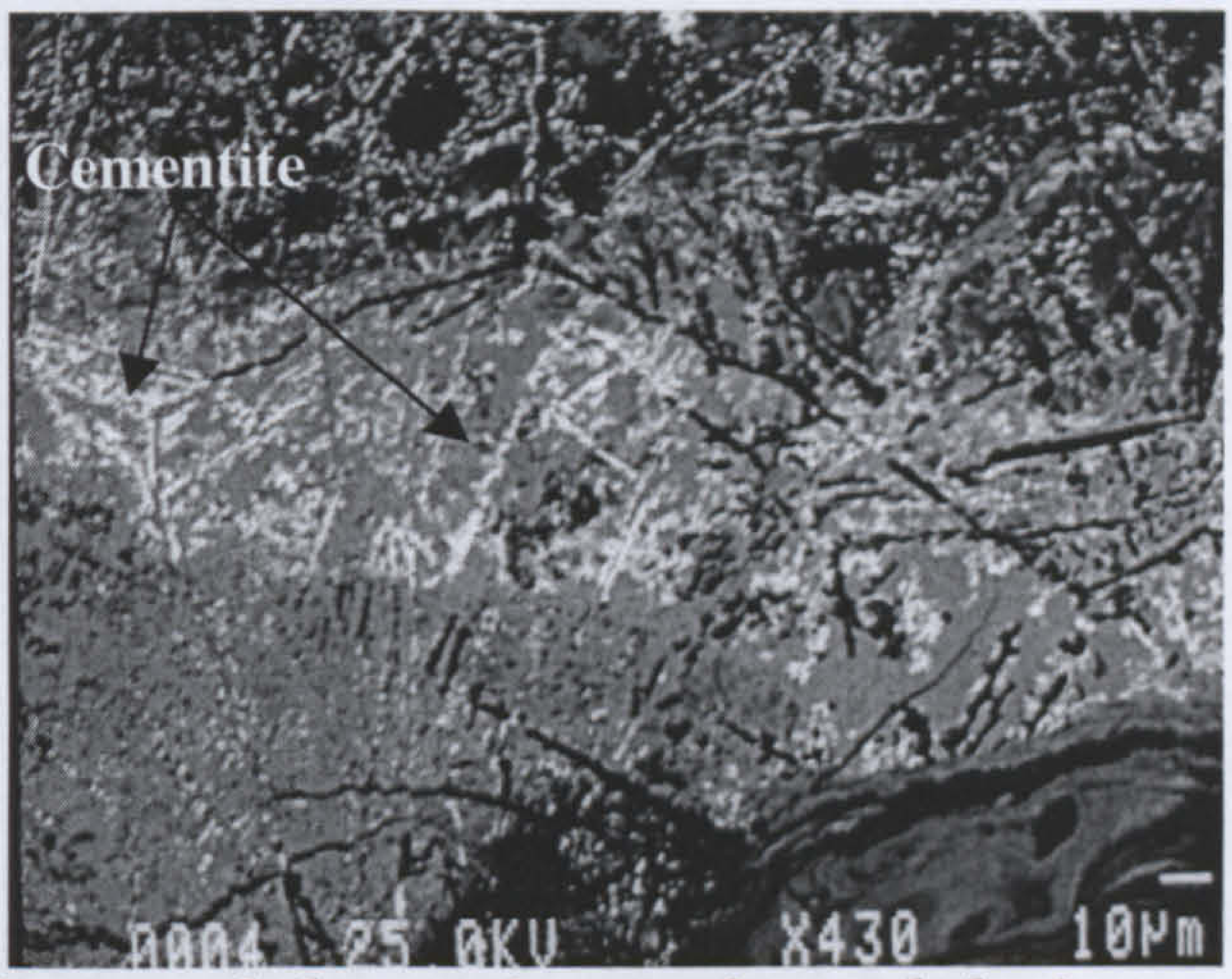


Figure 115: Backscattered electron image of corroded microstructure of RAS #2 with preserved cementite appearing as the light areas.

Discussion

The examination of the blades indicated that numerous different materials were used to produce blades in Central Asia and the materials do not appear to correlate with the location or time period attributed to the blade. The identification of four crucible steel blades is particularly important because the only other comparatively early crucible steel objects known from an archaeological context are those from Taxila.

Only six archaeological objects, the four blades from Kislovodsk, the Sasanian sword, and the blade attributed to Luristan have enough preserved steel and are documented in enough detail to compare the blades' microstructures with the aim of determining characteristics specific to crucible steel from archaeological contexts. The examination using optical microscopy indicated that they have four common characteristics:

1) A mottled appearance (after etching and under low magnification);
2) An homogenous carbon content throughout the sample;
3) Spheroidal or globular cementite well formed or just beginning;
4) No slag, or very little slag that contains less than 4% iron oxide.

All six blades had a mottled appearance after etching in Nital and examination at low magnification (around x60). At higher magnification spheroidal/globular cementite was observed. Gilmour also noted this mottled structure and spheroidal/globular cementite on historic objects made of crucible steel (Allan and Gilmour, 2000, 491). The mottled appearance is due to slight variations in the elemental compositions of the different regions, corresponding to the original location of dendrites and interdendritic regions that formed during the initial solidification of the metal. This feature is apparent on the six archaeological examples and historic objects, in addition to being a necessary feature of hypereutectoid Damascus steel, although the mottled pattern is not observed in Damascus steel because the cementite is now aligned in the interdendritic regions. The absence of this mottled pattern does not, however, necessarily rule out the use of crucible steel. Samuels (1980, 183) noted that in modern cast steels, the dendritic segregation could be eliminated if the steel undergoes a homogenizing annealing. It is reasonable to assume that the same mechanisms would apply to crucible steel made by traditional methods. However, Samuels (1980, 183) states that the time and temperature needed for full homogenisation is at least 45 hours at $1400^{\circ}C$ for phosphorus and longer for other elements such as manganese. It is unlikely that ancient craftsmen reached this high a temperature for that long a time. In addition, although the dendritic segregation may be present, it might not be readily observed. How the object was forged and how the object was sampled in relationship to the dendrites, could affect how well the dendrites are observed (Samuels, 1980, 181). These characteristics were also noted in historical crucible steel objects and therefore, these four characteristics could be used to discriminate between crucible steel and other types of steel that were once liquid. Further research on objects and replicated crucible steel may reveal additional traits.

The globular cementite alignment in KIS #2 is similar to Zschokke sword # 7 which had diffuse bands of elongated cementite particles. This suggests that, if etched, the sword would have had a faint Damascus pattern. This would make the sword the earliest known sword with a Damascus pattern. It is unclear if the sword was originally made with a separate handle or if the handle was a later addition, perhaps to mend a broken sword retrieved in battle. The presence of aligned cementite and the apparent Damascus pattern may explain why the tang/handle was riveted on rather than forge welded on. Forge welding is the process of heating two pieces of iron/steel together to form one piece. Typically the pieces are heated to white heat, around 1300-1400 $^{\circ}C$ and then forged together (Wagner, 1993, 274). This high temperature would adversely affect the spheroidal cementite thus eliminating any Damascus pattern observed on the surface of the blade. The smith might have been aware of the affect the heat would have had on the blade and might not have had the knowledge or resources available to reproduce the pattern. It may have been easier to rivet a handle on rather than eliminating the pattern and possibly producing a blade with inferior properties.

Chapter 5: Discussions and Conclusions

> *"Indian steel is the most prized for the material; but the best swords are made in Persia and in Syria".*
> (Elphinstone, 1972, 387)

The archaeological research results show that crucible steel was produced in at least five cities in Central Asia (Merv, Termez, Akhsiket, Pap, and Kuva) and used in at least five locations (Taxila, Kislovodsk, Nishapur, Northern Iran, and Kazakhstan), perhaps intermittently, from around the 1st century AD to the Mongol conquest. Historic and ethnographic accounts indicate that crucible steel was produced in Central Asia from at least the 3rd AD (e.g. Zosimos, see Craddock, 1998, 41-66) until the 19th century (e.g. Massalski, see Allan and Gilmour, 2000). The research results also demonstrate that the materials and techniques used to produce the crucible steel in Central Asia are significantly different than those used in south India/Sri Lanka. The conclusion must be that crucible steel was produced and used by people in various parts of Central Asia for at least 1,600 years, and during that time it was a native product, produced by specific methods and materials significantly different from those used in India or Sri Lanka. Crucible steel in Central Asia was clearly not exclusively an Indian import. This does not mean that no Indian crucible steel was imported into Central Asia, or that none from Central Asia was imported into India.

If the results determined above can be taken to reflect the norm, then the characteristics of crucible steel production in Central Asia, India and Sri Lanka can now be used to correctly identify and classify crucible steel remains found elsewhere. Both the Akhsiket and Merv crucible steel remains were initially incorrectly identified as the remains of glass production because the slag fin is glass-like in appearance and because the crucibles did not look like known crucible steel remains from India or Sri Lanka. The major differences are the shapes and materials used to produce the crucibles and the cooling rate of the ingots. In Central Asia flat-bottomed cylindrical crucibles were made out of refractory clay with inorganic temper, whereas in India and Sri Lanka the crucibles have rounded or pointed bottoms and are made out of ordinary clay with organic temper. The fact that the materials and process were not all the same could reflect that the technology had time to develop local variations and the craftsmen had adapted the technology to fit other established craft traditions, such as ceramic production and furnace designs.

All the evidence indicates that a variety of crucible charges could theoretically be used to produce a similar product. The chosen charge could reflect the availability of raw materials, such as the use of cast iron in Hyderabad (Lowe, 1989a). It also implies the use of recycled materials, such as the use of old horseshoes as reported by al-Beruni (Said, 1989, 219). The presumed use of small pieces of bloomery iron containing slag at Merv may be significant because it may suggest the use of lower quality/scrap bloomery iron. The result would be a higher quality product made out of low quality charge material. Similarly, Rehren and Papakhristu (2000) suggest a slag-rich bloomery iron as the raw material for the crucible steel industry at Akhsiket and Pap. For India and Sri Lanka, bloomery iron is also considered to be the metal charge, however, at least in some parts of India, the metal was forged into shape before being placed into the crucible (Anantharamu *et al.*, 1999, 20). In Central Asia, the carbon too could have been added by using ordinary domestic waste. Al-Beruni mentions pomegranate peels as an ingredient in the crucible charge (Said, 1989, 219). Indeed, during certain seasons such peels may have been plentiful and a cheap and effective source of carbon for the crucible charge. All in all, it appears as if of all the possible crucible charges, only one was continuously used during pre-modern times, namely bloomery iron and plant matter. Yet, the form of the bloomery iron and plant matter took, the addition of other materials such as manganese to the crucible charge, the size and shape of the crucibles and furnaces, in addition to the cooling rate of the metal, varied between different locations.

The term wootz has often been used to refer to any crucible steel produced in antiquity or by traditional methods, whereas the term pulad has a long history and its derivatives can be found in many Central Asian and European languages. I therefore feel the term wootz should only be used to refer to Indian crucible steel, whereas pulad should be used for Central Asian crucible steel. In addition, to provide clarity the adjective "crucible" should be added to Damascus steel, whenever the crucible variety of Damascus steel is being discussed. The use of these specific terms shall clarify further discussions.

The comparisons between the ingots from Central Asia and India/Sri Lanka in light of the Damascus steel replication experiments suggest that any Damascus pattern formed from the ingots would be different. In India and Sri Lanka, ethnographic reports state that ingots were removed from the furnace while the metal was liquid, quickly cooling the metal. The examination of an ingot by Wayman and Juleff (1999, 31) revealed primarily Widmanstätten cementite with a lesser amount of prior austenite grain boundary cementite, indicating rapid cooling, thus supporting the ethnographic reports. The remains of crucible steel ingots from Merv and Termez primarily have austenite grain boundary cementite with a small amount of cementite needles indicating that the ingots were cooled slowly. According to Verhoeven and Jones (1987, 178-179), their replication experiments indicate that the quality of the final pattern would be "strongly influenced by both the morphology of the Cm (cementite) before the forging and the time/temperature cycle employed in forging". Hence, the pattern which would appear on blades made from the fast cooled Indian/Sri Lankan ingots would be finer than the pattern made from slow cooled Central Asian ingots. Whereas, slow cooled ingots could be forged to create a fine pattern, a quickly cooled ingot could not produce a coarse pattern.

It is important to recall Bronson's observation that no first hand ethnographic reports from South India mention that the steel produces a Damascus pattern (Bronson, 1986, 39-40). In addition, the experiments performed by Wilkinson (1839, 389) on crucible steel ingots from Cutch, in Northern India on the India-Pakistan border, and from Salem, southern India, concluded that only the ingot from Cutch produced a good pattern, whereas the Salem sample had only a slight indication of a pattern. Therefore, the evidence from all archaeological, ethnographic, and replication experiments, indicates that crucible steel from South India/Sri Lanka, i.e. the areas associated with the terms wootz, produced crucible steel blades with either no pattern or a faint pattern only. Arguably, it is the coarse pattern, such as the Kara Khorasan pattern, that is most often associated with or characterizes "Damascus steel" (refer to Figures 97-100). As mentioned above, the archaeological evidence from Merv and Termez indicated that the microstructure of the ingots could have resulted in a coarse patterned blade. In addition, textual evidence (e.g. al-Beruni in Said, 1989, 219-220), and ethnographic reports (e.g. Abbott, 1884; Wilkinson, 1839, 38) all state that crucible steel blades with a good pattern were produced in Central Asia and Northern India, places where the term pulad (or related term) was used. Therefore, all the afore mentioned evidence indicates that crucible steel from Central Asia, which includes Northern India, could produced crucible steel blades with a coarse pattern, while the South Indian/Sri Lankan wootz ingots probably did not. This is contrary to the generally accepted opinion that Indian wootz steel was *primarily* used to produce "Damascus blades" (e.g. Verhoeven, 2001; Figiel, 1991, 7; Rostoker and Bronson, 1990, 130; Sachse, 1994, 67).

For the first time an argument has been made for a connection between the cooling rate of the ingot produced in the different locations and the coarse or fineness of the Damascus steel pattern. Further studies on the relationship between the dendrites produced during the cooling of the ingots, the affect of forging on these dendrites and the alignment of the cementite in bands, the spacing of the bands, and the final spacing of these bands as observed on the surface of the pattern, would be useful. Additional questions that remain to be studied included what causes the different colours of the "treads" and "background" colour described as appearing on Damascus steel blades. These colours are probably due to the refraction of light from different microstructures, the result of different etching depths, or the use of different types of etchants. The connection between microstructures, historical descriptions and the classification of Damascus steel patterns, could be used in future research to suggest trade routes, provenance, or original appearance of the blades. Future work with blacksmiths experienced in producing Damascus steel shall help determine additional aspects of the smithing process, which cannot be determined from archaeological remains, such as how much metal is lost during forging, the average length of time needed to forge a blade, and the amount of fuel needed during forging.

Textual evidence suggesting the appearance of a Damascus pattern appear in Sasanian texts (Smith, 1988, 14), Islamic texts (al-Beruni in Said, 1989) and from Chinese sources refer to steel made in Central Asia (see Laufer, 1917, 515). The examination of crucible steel blades from archaeological contexts, however, suggests that blades without a Damascus pattern were more prevalent that those with a pattern. Only the blade from Luristan (France-Lanord, 1969) could have had a clear pattern if etched, however, it is undated, therefore the 3rd - 4th century blade from Kislovodsk is the earliest known blade that could have had a Damascus pattern.

Many scholars, such as Piaskowski (1976) believe Damascus steel is one of the greatest achievements of early metallurgy. However, the technological step from crucible steel without a pattern, to that with one, would not necessarily have been a huge technological step. The Merv ingot (Chapter 1), the ingot from Sri Lanka (Wayman and Juleff, 1999, 31), and the replicated ingot (Verhoeven and Jones, 1987) all contain steadite indicating that the crucible steel ingots had to be forged below the austenite transition temperature or the ingot would have become brittle. In order to shape the blade, a cyclical forging process comparable to that used by Pendray (see Chapter 3) had to be employed. As long as the ingot contained the necessary trace elements, and the forging temperature remained below red heat, the process would promote the alignment of cementite. Therefore, the forging process used to produce the pattern was not a "new development" as such, but a consequence of the necessary forging method. Indeed, al-Beruni stated that the appearance of the pattern was an accident rather than a planned act (Said, 1989, 218).

The ability to melt iron/steel at such high temperature (over 1450^{O}C) can be considered a greater and more significant technological achievement than the formation of the Damascus pattern. Crucible steel with a Damascus pattern may or may not reflect a better quality blade than those without. Whereas the ability to construct a furnace, which could reach and maintain such high temperatures, in addition to producing crucibles that could withstand the high temperatures without failure, has much wider technological implications. The materials and methods used to construct the furnaces and crucibles could also be used to produce other objects, such as the Islamic Stonepaste wares. Therefore, the appearance of crucible steel not only necessitates the smelting of iron, but also the production of adequate furnaces and crucibles.

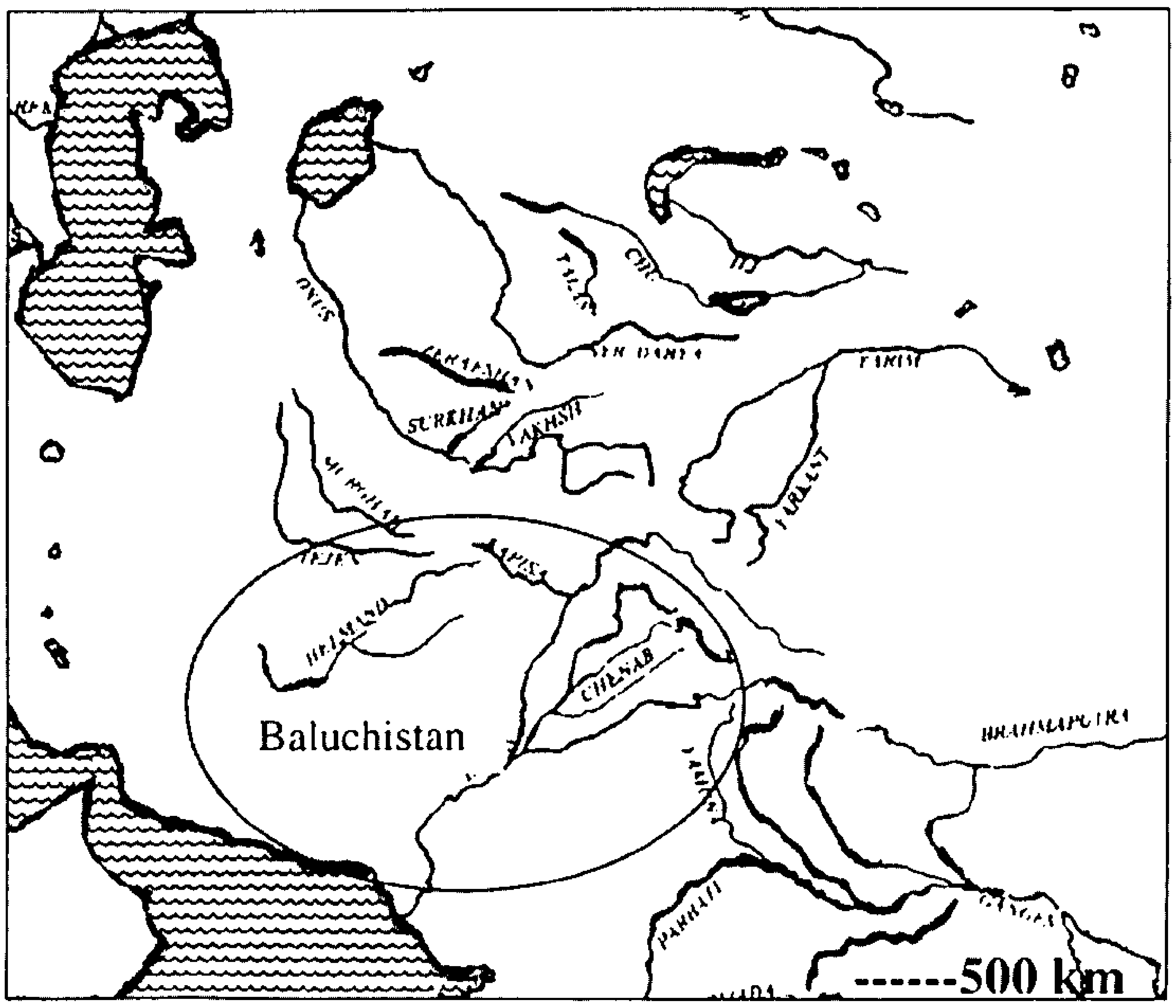
The identification of crucible steel blades from the Caucasus is the earliest evidence for the use of crucible steel in western Central Asia and demonstrates its presence there at least at three different times, 3rd-4th century AD, 7th century AD, and the late 11th century. It also illustrates the use of crucible steel to make different types of blades, double edged straight swords and sabres. Prior to this research, the characteristics of crucible steel objects made by pre-industrial methods and not exhibiting a Damascus pattern had not been considered in any detail. Establishing these characteristics allows the correct identification of crucible steel objects and to distinguish them from other types of steel that were once liquid, such as steel made in a Tatara furnace. Further research, however, is needed to build up a database of crucible steel objects in the hope of finding a single characteristic specific to crucible steel made in traditional societies. This research also identified features that remain in corrosion products, particularly uncorroded aligned cementite in a totally corroded matrix. This is particularly important because archaeological iron and steel tend to be for the most part corroded.

There are papers which state that crucible steel and Damascus steel were Arab traditions (e.g. Williams, 1997, 370; Weapons of the Islamic World Exhibition, 1991). While Arabs had a role in the history of crucible steel and Damascus steel, as traders and users of the steel, there is no evidence that they were producers or the originators of the process. Bronson (1986, 47) concluded that all early evidence of crucible steel production is Middle Eastern rather than Indian. However, the evidence reviewed in the previous chapters indicates that the early evidence is Central Asian, not Middle Eastern, nor Indian. Archaeological and textual evidence indicate that crucible steel was used within Central Asia and known outside of the area by the 3rd- 4th century AD. The 3rd-4th century AD crucible steel double-edged swords from Kislovodsk and the translation of Zosimo's 3rd century AD Alexandrian text discussing the production of crucible steel provide firm evidence for the use of crucible steel in Central Asia and its fame outside of this area by this time.

There is evidence suggesting that crucible steel was produced earlier. During the first century AD Pliny (died 79 AD) wrote ..."But of all the varieties of iron the palm goes to the Seres with their fabrics and skins. The second prize goes to Parthian iron; and indeed no other kinds of iron are forged from pure metal, as all the rest have a softer alloy welded with them" (Pliny, XXXIV translated by Rackham, 1995, 143-146). Bronson (1986) has argued that there is no evidence that the Seres were producing and exporting "wootz" to Rome. Those who discuss Pliny's statement seem to only be concerned about who the Seres were, probably the Tamil Cheres of South India (Juleff, 1990). However, the rest of Pliny's statement is perhaps even more telling. Regardless of who the Seres were, Pliny states that they, and the Parthians, are the only people to produce pure metal. The Parthians lived in Central Asia and although at the present time there is no evidence that the Parthians had crucible steel, there is ample evidence that it was in Central Asia a few centuries later. In addition, crucible steel has often been perceived as a high quality metal (see Chapter 3) and in later times crucible steel was frequently considered to be a "purified" metal (e.g. al-Kindi). Therefore, Pliny's praise may well be referring to crucible steel. The crucible steel association also lends support to the supposition that the Seres were the Tamil Cheres of South India, a people who are known to have been crucible steel producers although centuries later. Furthermore, around the 1st century AD Plutarch (46? - 120? AD) wrote, "While the Romans were in consternation at this din, suddenly their enemies dropped the coverings of their armour, and were seen to be themselves blazing in helmets and breastplates, their Margianian steel glittering keen and bright, and their horses clad in plates of bronze and steel" (Plutarch, 1915, 387). The fact that Plutarch mentions Margiana in connection with glittering steel is tempting because Margiana is an early name for Merv, and Merv produced crucible steel (see Chapter 1), at least during the early Islamic period. It may also be significant that the adjective used to describe the steel was glittering, because a term glittering was also used by al-Beruni centuries later in the context of crucible steel. In addition, Hadfield's analysis of what appears to be a crucible steel double-edged sword fragment from 1st century AD Taxila (Marshall, 1951, 536), and Pliny's 1st century AD comment about Parthian iron being "forged of pure metal" (Pliny, translated by Rackham, 1995, 143-146) point towards the use, or at least awareness of, crucible steel over a large geographic area during the 1st century AD.

The iron/steel blades from Luristan attributed to the first millennium BC should perhaps be re-examined using the distinguishing characteristics discussed in Chapter 4. Smith (1971, 52) argued that a blade attributed to Luristan, examined by France-Lanord (1969) was not crucible steel as suggested. In chapter 4 it was concluded that the blade was indeed crucible steel, although the date of its manufacture is uncertain. Spheroidal/globular cementite is commonly found in crucible steel and Damascus steel objects, and has also been observed in some blades from Luristan. No one has considered that crucible steel production may have been used during the first millennium BC, but in light of this research, the possibility should not be dismissed.

The initial origin of crucible steel probably lies centuries earlier than the first few centuries AD, as it would probably have taken decades, perhaps centuries, for the knowledge of crucible steel production to spread to other workshops, as well as the awareness of this apparently different type of "iron" to become known and develop a positive reputation outside of the immediate production areas. Without more field research it is not possible to determine where or when the technology of crucible steel originated. However, a possible location and time period where future research should concentrate within lands that are roughly around the Indus Valley and Baluchistan, an area that sometimes was under Indian, and other times Persian, rule (Map 12).



Map12: Proposed location for area originating crucible steel.

A prerequisite for manufacturing crucible steel is the production of iron on a regular basis, suggesting a date after the beginning of the 1st millennium BC and probably after around 500 BC, by which time iron is thought to have been produced on a somewhat regular basis in eastern Central Asia (Pigott, 1985, 626). However, there is no reason why crucible steel could not have developed at the same time as iron smelting was developing out of Bronze Age copper refining and casting traditions. Copper-alloy refining involves placing the smelted metal into a crucible and heating it. The slag separates thus refining the metal by removing slag and other impurities trapped in the metal during the smelting process. In addition, the liquid metal may be stirred with green wood which produce gasses reducing copper oxides to metal that would otherwise make the metal brittle when cast (Hodges, 1989, 70).

Removing slag from smelted iron requires the same materials, (i.e. a ceramic crucible, a furnace, and wood or other carbonaceous matter) but by a slightly different process. Iron has a higher melting temperature and oxidizes more readily than copper therefore higher furnace temperatures are needed and the crucible needs to be closed. However, by adding pieces of carbonaceous material to the iron and placing a lid on the crucible, the iron carbonises and becomes steel, which requires a lower temperature to become liquid, then the slag rises to the surface thus refining the steel. Therefore, the only differences between refining copper in a crucible and refining iron is the use of a lid and placing carbonaceous material into the crucible rather than stirring with green wood. The similarity is even more pronounced if the smith is using a broken iron bloom and pieces of wood, such as that the proposed method used at Early Islamic Merv.

Further supporting the argument that crucible steel may have developed out of refining smelted metal is the idea that crucible steel is "pure" or "refined" metal, proposed by Pliny and later by al-Kindi. The concept of "purifying" the iron may be a significant clue to its origins not only because of the argument regarding the development from copper refining, but because a large part of Zoroastrianism, practiced in south-eastern Central Asia from the last half of the first millennium BC onwards, was concerned with purification and fire worship. One may speculate that the priests and the craftsmen/scholars would have studied the properties of materials and fire.

If the term "pulad" did indeed originate from a Sanskrit based language as proposed in Chapter 3 then the proposed etymology could be used to support the hypothesis that crucible steel originated in a region where a Sanskrit language was spoken and Zoroastrianism or a related religion, was practiced. The similarities between the languages and religious beliefs found in the Vedas, written in Sanskrit and used in India, and the Zoroastrian Avesta written in Avestan and used in Eastern Iran/Persia (Asthana, 1976, 121) further suggest that crucible steel might have developed somewhere between Northern India and Eastern Persia/Central Asia during the first half of the 1st millennium BC.

Regardless from where and when crucible steel may have originated, it was known since at least the 3rd century AD. Information regarding the spread of the technology, ingots and/or finished objects by trade is sparse. Al-Kindi and other writers provide some information on production and distribution centres, however the picture of the spread of the material and/or technology is incomplete. Apparently over the next thousand plus years, crucible steel spread to the Middle East, Africa, and Europe as far as Spain with Islamic armies, into Austria with Ottoman Turks, and occasionally as far west as England through trade. Crucible steel objects also spread northeast to Siberia and possibly as far east as China, Korea, and perhaps Japan. However, it seems that the technological know-how remained restricted to Central Asia and India.

Perhaps it was the different forging traditions that caused the difficulties in producing crucible steel with the desired Damascus pattern. It is perhaps the presence of steadite that caused the European smiths, such as Moxon (1677), so much difficulty in forging crucible steel. European blacksmithing traditionally used a method of high temperature forging which was not applicable to crucible steel that contained steadite, because the ingot would have cracked. In addition, ethnographic and replication experiments indicate that the ingot would have had to have been annealed before forging, unlike an ingot of carburized bloomery iron or directly smelted steel. Low temperatures, repeated forging and air cooling or low temperature quenching, were all necessary parts of the crucible and Damascus steel forging process, in contrast to other ferrous metallurgical traditions which used high temperature forging and high temperature quenching.

It is ironic that while crucible steel and Damascus steel research was being undertaken in Europe during the 18th and 19th centuries to discover how the Damascus pattern was formed, because the pattern was associated with the alleged superior qualities of the steel, the traditional technology was at the same time dying out in Central Asia and India/Sri Lanka, probably because of the availability of cheap imported European steel. The last known record of crucible steel production in Central Asia is Massalski's report from Bukhara during the 19th century (see Allan and Gilmour, 2000, 535). Other accounts include Abbotts's (1884) account from north India during the mid 19th century. Although small pockets of production may have continued for a few years into the early 1900s, the dawn of the 20th century saw the death of crucible steel production in traditional societies after around 2000 years or so of production.

The legacy of crucible and Damascus steel nevertheless lives on today as alloy steels. Alloy steels were initially developed during the 18th and 19th century during research into mechanisms that cause the Damascus steel pattern, and they are still widely produced today.

Year	Context	AKA	Small	Sam	Sec	Weight	Crucible	Slag	Prills	Cu	Other	Notes
	7.F.II	MGK 4 surface	8052	51	E		☐	☐	☐	☑	☐	cu
1993	7.F.II	A3.8				21.5	☑	☑	☑	☐	☐	wall
1993	7.F.II	A3.5				7.1	☑	☑	☑	☐	☐	wall
1992	7.F.II	AC.26.93 G				33.4	☐	☐	☐	☐	☑	furnace wall
1992	7.F.II	AC.26.93 J. II				13.7	☑	☐	☐	☐	☐	base
1992	7.F.II	AC.26.93.I. I				41.3	☐	☐	☐	☐	☑	furnace wall
1992	7.F.II	AC.26.93. A.II				19	☑	☐	☐	☐	☐	wall
1992	7.F.II	AC.26.93.A. V				16.7	☑	☐	☐	☐	☐	lid
1994	7.E.II.C					19	☐	☐	☐	☐	☑	lump (same as 47?)
1994	7.F.II.A					1.4	☐	☐	☐	☐	☑	lump
1994	7.F.II.O					16.2	☐	☐	☐	☐	☑	lump
1994	7.F.II.E					76.1	☐	☐	☐	☐	☑	lump
1994	8.F.IV.E					26.5	☐	☐	☐	☐	☑	lump
1994	7.E.II.J					5.6	☐	☐	☐	☐	☑	lump
1994	8.F.IV.G					8.7	☐	☐	☐	☐	☑	lump
1994	7.E.II.F					42.9	☐	☐	☐	☐	☑	lump
1994	7.E.II.I					9.7	☐	☐	☐	☐	☑	lump
1994	7.E.II	39 C	8048	39	C	4.6	☐	☐	☐	☑	☐	Cu
1994	7.E.II		8048	39	all	4.6	☐	☐	☐	☑	☐	Cu (x 6)
1994	7.F.II	MGK 4 surface	8052	51	all	23	☐	☐	☐	☑	☐	Cu (x18)
1994	7.F.II	MGK 4 surface	8052	51	B		☐	☐	☐	☑	☐	Cu
1994	7.F.II	MGK 4 surface	8052	51	A		☐	☐	☐	☑	☐	Cu slag
1994	7.E.II.A					6.3	☐	☐	☐	☐	☑	iron/slag
1994	7.E.II.B					6.2	☑	☐	☐	☑	☑	different crucible
1994	7.E.II.D					123.2	☐	☐	☐	☐	☑	magnetic slag
1994	7.E.II.E					3.5	☑	☐	☐	☑	☑	crucible similar to 130
1994	7.E.II.G					19.3	☐	☐	☐	☐	☑	iron and mud
1994	7.E.II.H					20	☑	☐	☐	☐	☐	another different crucible
1994	7.E.II.K					1.8	☐	☐	☐	☐	☑	magneitic slag

Year	Context	AKA	Small	Sam	Sed	Weight	Crucible	Slag	Prills	Cu	Other	Notes
1994	7.F.II.K	MGK 4 surface				9.1	☐	☐	☐	☑	☑	cu and mud
1994	7.F.II.L	MGK 4 surface				1.3	☐	☐	☐	☑	☐	cu slag
1994	7.F.II.M	MGK 4 surface				.7	☐	☐	☐	☑	☐	cu
1994	7.F.II.N	MGK 4 surface				2.5	☐	☐	☐	☑	☐	cu slag
1994	7.F.II.P					4.2	☐	☐	☐	☐	☑	magnetic slag
1994	7.F.II.Q					2.5	☐	☐	☐	☐	☑	iron lump
1994	7.F.II.R					3.4	☐	☐	☐	☐	☑	iron lump
1994	7.F.II.S					3.1	☐	☐	☐	☐	☑	vitrified comglomerate (furnace floor?)
1994	8.F.II.A					161.6	☐	☐	☐	☐	☑	smithing hearth bottom?
1994	8.F.II.B					365.6	☐	☐	☐	☐	☑	smithing hearth bottom?
1994	8.F.IV.A					60.8	☐	☐	☐	☐	☑	magnetic slag
1994	8.F.IV.B					4.4	☐	☐	☐	☐	☑	magnetic slag
1994	8.F.IV.C					3.2	☐	☐	☐	☐	☑	magnetic slag
1994	8.F.IV.D					11.5	☐	☐	☐	☐	☑	magnetic slag
1994	8.F.IV.F					3.5	☐	☐	☐	☐	☑	magnetic slag
1994	8.F.IV.H					2.2	☐	☐	☐	☐	☑	magnetic slag
	7.F.I		2983			38	☑	☐	☐	☐	☐	base
	7.G.IV		3003			4.9	☐	☐	☐	☑	☐	cu and slag
	7.G.IV		3003			3.9	☐	☐	☐	☑	☐	cu and slag
	7.G.IV		3003			3.3	☐	☐	☐	☑	☐	cu and slag
	7.G.IV		3003			.9	☐	☐	☐	☑	☐	cu and slag
	7.G.IV		3003			3.6	☐	☐	☐	☑	☐	cu slag (x5)
	7.G.IV		3003			25.8	☐	☐	☐	☑	☐	cu fragments
	8.G.III/IV		2984			17.5	☑	☐	☐	☐	☐	lid
	8.G.III/IV		2985			31	☑	☐	☐	☐	☐	different lid
	8.G.III/IV		2986			118.2	☑	☐	☐	☐	☐	wall
	7.F.I		2991			38	☑	☐	☐	☐	☐	base
1992	7.F.II	AC.26.93.A.I				13.5	☑	☐	☐	☐	☐	lid
1992	7.F.II	AC.26.93.A.III				19.2	☑	☐	☐	☐	☐	wall

Year	Context	AKA	Small	Sam	Sed	Weight	Crucible I	Slag	Prills	Cu	Other	Notes
1992	7.F.II	AC.26.93.A.IV				18.8	☑	☐	☐	☐	☐	lid
1992	7.F.II	AC.26.93.A.VI				3.8	☑	☐	☐	☐	☐	wall
1992	7.F.II	AC.26.93.A.VII				3.3	☑	☐	☐	☐	☐	lid
1992	7.F.II	AC.26.93.B				394.3	☐	☐	☐	☐	☑	furnace wall
1992	7.F.II	AC.26.93.C				189.6	☑	☐	☐	☐	☐	base
1992	7.F.II	AC.26.93.D				71.3	☑	☐	☐	☐	☐	base
1992	7.F.II	AC.26.93.E/ MGK 4 surface				3.2	☐	☐	☐	☑	☐	cu fragment
1992	7.F.II	AC.26.93.F				40.2	☑	☐	☐	☐	☐	base
1992	7.F.II	AC.26.93.H.I				1.9	☐	☑	☐	☐	☐	slag
1992	7.F.II	AC.26.93.H.II				13.7	☑	☐	☐	☐	☐	wall
1992	7.F.II	AC.26.93.I.II				11.8	☐	☐	☐	☐	☑	fired brick
1992	7.F.II	AC.26.93.J.I				15.9	☑	☐	☐	☐	☐	base
1993	7.F.II	A3.1					☐	☐	☐	☐	☑	furnace wall
1993	7.F.II	A3.2				12.8	☑	☐	☐	☐	☐	base
1993	7.F.II	A3.3					☑	☐	☐	☐	☐	wall
1993	7.F.II	A3.4				19.2	☑	☐	☐	☐	☐	wall
1993	7.F.II	A3.6					☑	☐	☐	☐	☐	warped crucible wall
1993	7.F.II	A3.7				11.6	☑	☐	☐	☐	☐	wall
1993	7.F.II	A3.9					☑	☐	☐	☐	☐	wall

ID	Year	Context	Small Finds	Section	Weight	Crucible	Slag	Prills	Cu	Other	Notes
1	1993	Surface				☑	☑	☑	☐	☐	
2	1993	Surface				☑	☑	☐	☐	☐	
3	1993	2.2				☐	☑	☐	☐	☐	
4	1993	Surface				☑	☑	☑	☐	☐	
5	1993	Surface				☑	☑	☑	☐	☐	
6	1993	Surface				☐	☑	☑	☐	☐	
7	1993	Surface				☐	☑	☑	☐	☐	
8	1993	Surface				☐	☑	☑	☐	☐	
9	1993	Surface				☐	☑	☑	☐	☐	
10	1993	Surface				☐	☑	☑	☐	☐	
11	1993	Surface				☐	☑	☑	☐	☐	
12	1993	Surface				☐	☑	☑	☐	☐	
13	1993	Surface				☐	☑	☑	☐	☐	
14	1993	Surface				☐	☑	☑	☐	☐	
15	1993	Surface				☐	☑	☑	☐	☐	
16	1993	Surface				☐	☑	☑	☐	☐	
17	1993	Surface				☐	☑	☑	☐	☐	
18	1993	Surface				☑	☑	☑	☐	☐	
19	1993	Surface				☑	☑	☑	☐	☐	
22	1993	Surface				☐	☑	☑	☐	☐	
23	1993	Surface				☑	☑	☐	☐	☐	
24	1993	Surface				☑	☑	☑	☐	☑	
29	1993	Surface				☑	☑	☐	☐	☐	
31	1993	Surface				☑	☑	☐	☐	☐	
32	1993	Surface				☐	☑	☑	☐	☐	
33	1993	Surface				☑	☑	☑	☐	☐	
34	1993	Surface				☐	☐	☐	☐	☑	
35	1993	Surface				☐	☑	☐	☐	☐	
36	1993	Surface			53	☑	☐	☐	☐	☐	base

ID	Year	Context	Small Finds	Section	Weight	Crucible	Slag	Prills	Cu	Other	Notes
37	1993	Surface			20.2	☑	☐	☐	☐	☐	lid
38	1993	1			14.5 g.	☑	☑	☐	☐	☐	
40	1993	Surface				☐	☐	☐	☐	☑	black glaze
50		Surface				☑	☐	☐	☐	☐	luting
51		Surface				☐	☐	☐	☐	☑	Furnace wall
52		Surface				☐	☐	☐	☐	☑	
53		Surface				☐	☐	☐	☐	☑	lump
54		Surface				☐	☐	☐	☐	☑	dirt
55		Surface				☐	☑	☑	☐	☐	
56		Surface				☐	☑	☑	☐	☐	
57		Surface				☐	☑	☑	☐	☐	
58		Surface				☐	☑	☑	☐	☐	
59		Surface				☐	☑	☑	☐	☐	
60		Surface				☐	☑	☑	☐	☐	
61		Surface				☐	☑	☑	☐	☐	
62		Surface				☐	☑	☑	☐	☐	
63		Surface				☐	☑	☑	☐	☐	
64		Surface				☐	☑	☑	☐	☐	
65		Surface				☐	☑	☑	☐	☐	
66		Surface				☐	☑	☑	☐	☐	
67		Surface				☐	☑	☑	☐	☐	
68		Surface				☐	☑	☑	☐	☐	
69	1994	15	8037	A	5.6	☐	☐	☐	☑	☐	Cu
71	1994	2	8050		1.9	☐	☐	☐	☑	☐	Cu
73	1994	12				☐	☐	☐	☑	☐	Cu
74	1994	2			60.8	☑	☐	☐	☐	☐	lid
75	1994	34			37	☑	☐	☐	☐	☐	lid
76	1994	34		a	8.3	☐	☐	☐	☐	☑	conglomerate with iron
77	1994	34		b	3.7	☐	☐	☐	☐	☑	

ID	Year	Context	Small Finds	Section	Weight	Crucible	Slag	Prills	Cu	Other	Notes
78	1994	34		c	2.4	☐	☐	☐	☐	☑	
79	1994	6-7			32.4	☑	☐	☐	☐	☐	lid
80	1994	6-7			30.4	☑	☑	☐	☐	☐	lid with wall
81	1994	11			51.5	☑	☐	☐	☐	☐	lid from "section"
82	1994	2			39	☑	☐	☐	☐	☐	base
83	1994	20				☑	☐	☐	☐	☐	
84	1994	42			44.9	☑	☐	☐	☐	☐	lid
85	1994	42			58.4	☑	☐	☐	☐	☐	lid with wall (x3)
86	1994	6			34.8	☑	☐	☐	☐	☐	lid
87	1994	29			172.4	☑	☐	☐	☐	☐	base
88	1994	1			18.2	☑	☐	☑	☐	☐	wall
89	1994	1			18.3	☑	☐	☑	☐	☐	wall
90	1994	1			17.7	☐	☐	☐	☐	☑	iron lumps (x80)
91	1994	3			31.5	☑	☐	☐	☐	☐	wall
92	1994	3			35.1	☐	☐	☐	☐	☑	frunace wall (x3)
93	1994	5		a	11.1	☐	☐	☐	☐	☑	iron lumps
94	1994	5		b	5.3	☐	☐	☐	☐	☑	iron lumps
95	1994	11			7.2	☐	☐	☐	☐	☑	iron lumps (x8)
96	1994	14			10.8	☑	☐	☐	☐	☐	fragments
97	1994	14		a	21.1	☐	☐	☐	☐	☑	iron lumps
98	1994	14		b	7.7	☐	☐	☐	☐	☑	iron lumps
99	1994	14		c	2.8	☐	☐	☐	☐	☑	iron lumps
100	1994	14		d	.7	☐	☐	☐	☐	☑	iron lumps
101	1994	33	8033		4.6	☐	☐	☐	☐	☑	iron ring (x2)
102	1994	12	8043		.4	☐	☐	☐	☑	☐	Cu
104		Surface				☐	☑	☑	☐	☐	
105	1994	12	8041		1.7	☐	☐	☐	☑	☐	Cu scale fragment
106	1994	33	8045		6.5	☐	☐	☐	☐	☑	Iron rod
107	1994	42	8061	a	4.4	☐	☐	☐	☐	☑	Iron rod

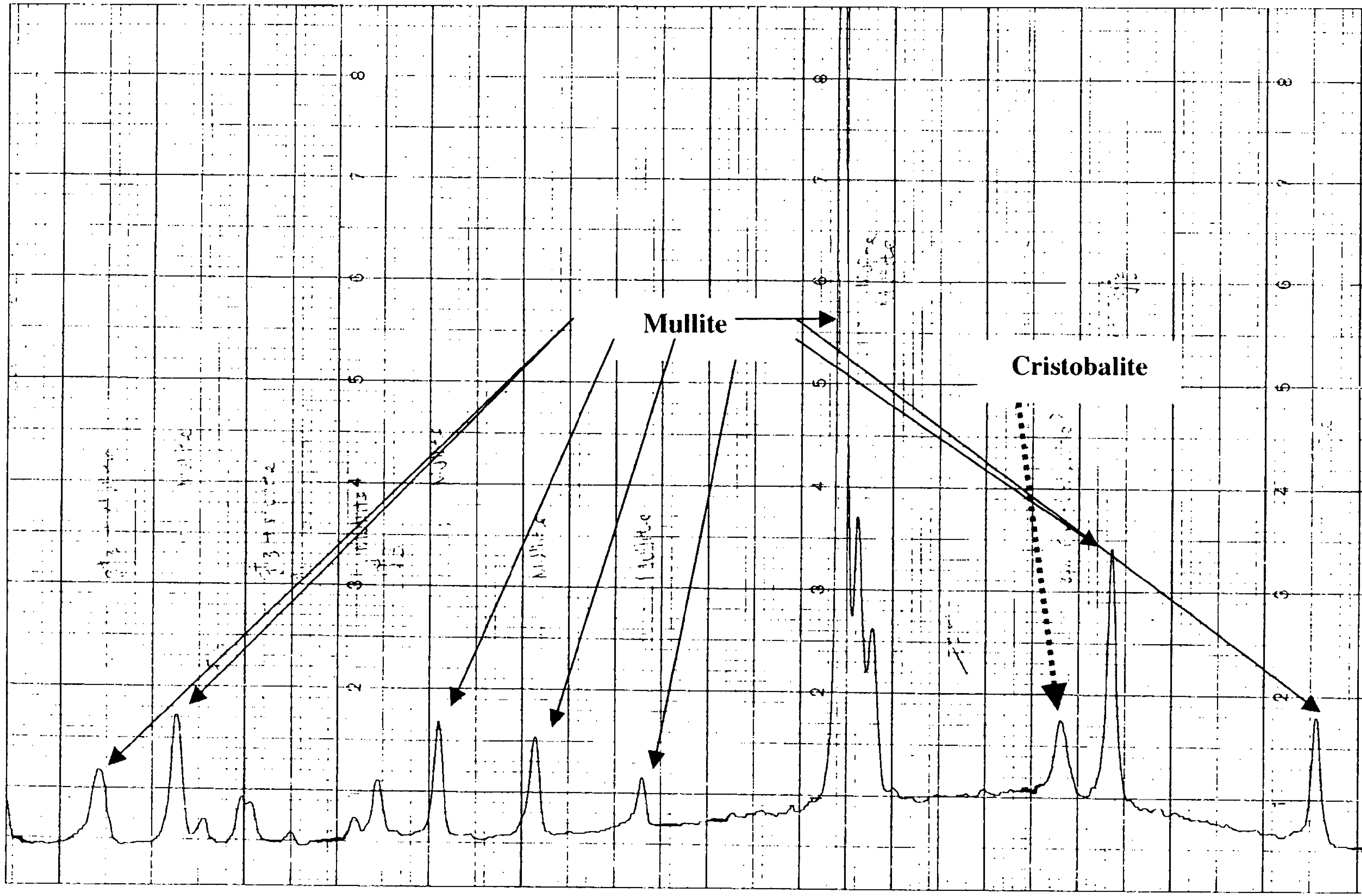
ID	Year	Context	Small Finds	Section	Weight	Crucible	Slag	Prills	Cu	Other	Notes
108	1994	42	8061	b	1.5	☐	☐	☐	☐	☑	Iron rod
109	1994	42	8057		12.9	☐	☐	☐	☐	☑	Iron fragments (x20)
110	1994	42	8059		4.5	☐	☐	☐	☐	☑	Iron nail
111	1994	42	8058	a	1.2	☐	☐	☐	☐	☑	iron rod
112	1994	42	8058	b	2	☐	☐	☐	☐	☑	iron rod
113	1994	42	8060		3.6	☐	☐	☐	☐	☑	iron lump
114	1994	3	8055	a	8.7	☐	☐	☐	☐	☑	iron fragments (x7)
115	1994	3	8055	b	2.2	☐	☐	☐	☐	☑	iron fragments
116	1994	3	8055	c	1.3	☐	☐	☐	☐	☑	iron fragments
117	1994	3	8055	d	.9	☐	☐	☐	☐	☑	iron fragments
118	1994	3	8055	e	.6	☐	☐	☐	☐	☑	iron fragments
119	1994	42	8044		3.4	☐	☐	☐	☑	☐	Cu
120	1994	114	8062		2	☐	☐	☐	☐	☑	iron fragment
123	1994	15	8037	b	1.8	☐	☐	☐	☐	☐	
124	1994	15	8037	c	.3	☐	☐	☐	☐	☐	
207	1993	surface				☐	☐	☐	☐	☑	furnace wall
208	1993	surface			179	☑	☐	☐	☐	☐	base
209	1993	surface				☐	☐	☐	☐	☑	furnace wall
210	1993	surface				☐	☐	☐	☐	☑	furnace wall
211	1993	surface				☐	☐	☐	☐	☑	furnace wall
212	1993	surface				☐	☐	☐	☐	☑	furnace wall
213	1993	surface			8.7	☑	☐	☐	☐	☐	lid
214	1993	surface			9.1	☑	☐	☐	☐	☐	lid
215	1993	surface			18.2	☑	☐	☐	☐	☐	warped lid
216	1993	surface			20.5	☑	☐	☐	☐	☐	wall
217	1993	surface			16.2	☑	☐	☐	☐	☐	pad
218	1993	surface				☑	☐	☐	☐	☐	
219	1993	surface				☑	☐	☐	☐	☐	lid
220	1993	surface				☐	☐	☐	☐	☑	clear glass with blue rim

ID	Year	Context	Small Finds	Section	Weight	Crucible	Slag	Prills	Cu	Other	Notes
221	1993	surface				☐	☐	☐	☐	☑	green glass
222	1993	surface				☐	☐	☐	☐	☑	green glass
223	1993	surface				☐	☐	☐	☐	☑	clear glass
224	1993	surface				☐	☐	☐	☐	☑	green glass
225	1993	surface				☐	☐	☐	☐	☑	green glass
226	1993	surface				☐	☐	☐	☐	☑	green glass
227	1993	surface				☑	☑	☐	☐	☐	
228	1993	surface	A2.13			☐	☐	☐	☑	☐	
236	1993	2.2				☐	☐	☐	☐	☑	pipe fragment
237	1993	2.2				☐	☐	☐	☐	☑	furnace wall
238	1993	2.2				☑	☐	☐	☐	☐	wall
239	1993	surface				☐	☐	☐	☐	☑	pip fragment
240	1993	surface				☐	☐	☐	☐	☑	furnace wall
241	1995	1 76			.9	☐	☐	☐	☐	☑	iron slag
242	1995				.13	☐	☐	☐	☐	☑	
243	1995				.29	☐	☐	☐	☐	☑	
244	1995				.21	☐	☐	☐	☐	☑	
245	1995				.72	☐	☐	☐	☐	☑	
246	1995				.57	☐	☐	☐	☐	☑	
247	1995				.26	☐	☐	☐	☐	☑	
248	1995				.23	☐	☐	☐	☐	☑	
249	1995				.2	☐	☐	☐	☐	☑	
250	1995				41.9	☐	☐	☐	☑	☐	cu slag
251	1995				25.9	☑	☐	☐	☐	☐	and mud
252	1995				37.35	☐	☐	☐	☑	☐	Cu fragments
253	1995	1 76			9	☑	☐	☐	☐	☐	wall
254	1995	86			2	☑	☐	☐	☐	☐	base
255	1995	2	8096		50.5	☐	☐	☐	☐	☑	fired mud
256	1995		2589		16.36	☐	☐	☐	☑	☐	cu slag

ID	Year	Context	Small Finds	Section	Weight	Crucible	Slag	Prills	Cu	Other	Notes
257	1995		2590		4.9	☐	☐	☐	☑	☐	cu slag
258	1995	1			138.3	☐	☐	☐	☑	☐	crucible used for Cu?
259	1995	62 74			204.44	☐	☐	☐	☐	☑	crucible and dirt
260	1995	12			2.3	☐	☐	☐	☑	☑	Fe and cu
261	1995	1			1.23	☐	☐	☐	☑	☐	(x 16)
262	1995				16.09	☐	☐	☐	☑	☐	
263	1995				1.3	☐	☐	☐	☑	☐	
264	1995				.37	☐	☐	☐	☑	☐	
265	1995				.43	☐	☐	☐	☑	☐	
266	1995				.2	☐	☐	☐	☑	☐	
267	1995				.3	☐	☐	☐	☑	☐	
268	1995				.37	☐	☐	☐	☑	☐	
269	1995	1		C	23.41	☐	☐	☐	☑	☐	cu fragments
270	1995	29 14?			.2	☐	☐	☐	☑	☐	
271	1995	10 4			1.2	☐	☐	☐	☐	☑	slag(x8)
272	1995	9? 3			6.4	☑	☑	☑	☐	☑	(x50) misc.
273	1995	62			8.4	☐	☐	☐	☑	☐	slag
274	1995				11.7	☐	☐	☐	☑	☐	slag
275	1995				31.8	☐	☐	☐	☐	☑	fired mud
276	1995				5.1	☐	☐	☐	☑	☐	
277	1995	1				☐	☐	☐	☑	☑	(1 of 20) Cu and vitrified mud
278	1996		3153a			☐	☐	☐	☐	☐	
279	1996		3153b			☐	☐	☐	☐	☑	
280	1996		3153c			☐	☐	☑	☐	☐	
281	1996		3153d			☐	☐	☑	☐	☐	
282	1996		3153e			☐	☐	☐	☐	☑	
283	1996		3153f			☐	☐	☐	☐	☑	heated ore
284	1996		3153g			☐	☐	☐	☐	☑	
285	1996		3153h			☐	☐	☑	☐	☐	

ID	Year	Context	Small Finds	Section	Weight	Crucible	Slag	Prills	Cu	Other	Notes
286	1996		3153i			☐	☐	☑	☐	☐	
287	1996		3153j			☐	☐	☑	☐	☐	
288	1996		3153k			☐	☐	☐	☐	☑	heavy, heated ore
289	1996		3153l			☐	☐	☑	☐	☐	
290	1996		3153m			☐	☐	☑	☐	☐	
291	1996		3153n			☐	☐	☐	☐	☑	
292	1996		3153o			☐	☐	☐	☐	☑	
293	1996		3153p			☐	☐	☐	☐	☑	
294	1996		3153q			☐	☐	☐	☐	☑	
295	1996		3153r			☐	☐	☐	☐	☑	
296	1996		3153s			☐	☐	☐	☐	☑	
297	1996		3153t			☐	☐	☐	☐	☑	
298	1996		3153u			☐	☐	☐	☐	☑	
299	1996		3153v			☐	☐	☑	☐	☐	
300	1996		3153w			☐	☐	☑	☐	☐	
301	1996		3153x			☐	☐	☑	☐	☐	
302	1996		3153y			☐	☐	☑	☐	☐	
303	1996		3153z			☐	☐	☑	☐	☐	
304	1996		214			☐	☐	☑	☐	☐	
305	1996		214			☐	☐	☑	☐	☐	
306			6522			☐	☐	☐	☐	☐	
307			8416			☐	☐	☐	☐	☑	iron
308						☐	☐	☐	☐	☐	
309	1995	1		all	73.5	☐	☐	☐	☑	☑	(x20) Cu and vitrified mud
310	1996	116				☐	☐	☐	☑	☐	

Appendix C: Example of X-ray Diffraction Pattern of Merv Crucibles



Appendix D: EPMA of Merv Crucible Fragments

100 micron square area

Lids	***sample #***	***area***	***CaO***	***K_2O***	***Na_2O***	***SiO_2***	***FeO***	***Al_2O_3***	***MgO***	***TiO_2***	**Totals**
	388	lid a	0.29	2.9	0.04	62	1.094	34	0.12	0.553	102
	388	lid b	0.54	3.5	0.19	58	0.498	30	0.12	0.687	93
	388	lid c	0.31	3.0	0.09	59	0.779	26	0.14	0.706	90
	388	lid d	0.78	3.6	0.24	60	0.479	29	0.29	0.546	94
average	***388***	***lid***	***0.5***	***3.3***	***0.14***	***60***	***0.71***	***30***	***0.17***	***0.62***	***95***
standard deviation			*0.2*	*0.4*	*0.09*	*2*	*0.29*	*3*	*0.08*	*0.09*	
	388	yellow inclusion	0.01	0.1	0	96	0.011	0	0	0.005	97
	388	bright area	16.6	5.6	1.05	49	0.134	17	1.11	0.368	91
	78	lid a	0.6	5.3	0.57	64	0.722	25	0.34	0.537	97
	78	lid b	0.22	2.8	0.23	53	0.992	35	0.16	0.545	93
	78	lid c	0.5	4.3	0.48	62	1.333	27	0.37	0.667	97
	78	lid d	0.67	5.6	0.5	67	0.58	21	0.55	0.154	96
average	***78***	***lid***	***0.5***	***4.5***	***0.44***	***62***	***0.91***	***27***	***0.35***	***0.48***	***96***
standard deviation			*0.2*	*1.2*	*0.15*	*6*	*0.33*	*6*	*0.16*	*0.22*	
unusual features	78	edge	0.29	2.9	0.34	56	0.654	32	0.2	0.453	94
	78	interesting	0.26	2.5	0.12	55	2.732	34	0.4	0.641	96
	78	lid/glaze	15	3.5	0.52	48	0.055	15	0.78	0.314	83
	78	weird	0.54	3.3	0.22	47	0.433	34	0.8	0.807	88
	392	lid a	2.41	4.0	0.17	63	1.695	23	0.65	0.574	96
	392	lid c	0.37	4.2	0.12	76	0.484	15	0.18	0.536	97
	392	lid d	1.74	4.6	0.38	56	0.905	28	0.48	0.666	93
average	***392***	***lid***	***1.5***	***4.2***	***0.22***	***65***	***1.03***	***22***	***0.44***	***0.59***	***95***
standard deviation			*1*	*0.3*	*0.14*	*10*	*0.61*	*7*	*0.23*	*0.07*	
	double lid	lid a	0.58	5.5	0.23	67	0.586	19	0.28	0.305	93
	double lid	lid b	0.68	8.1	0.37	66	0.159	18	0.26	0.092	94
	double lid	lid c	0.84	7.4	0.6	68	0.085	18	0.34	0.004	95
average	***double lid***	***lid***	***0.7***	***7.0***	***0.4***	***67***	***0.28***	***18***	***0.29***	***0.13***	***94***

Appendix D: EPMA of Merv Crucible Fragments

Walls	sample #		CaO	K_2O	Na_2O	SiO_2	FeO	Al_2O_3	MgO	TiO_2	Totals
	A.6.13	wall a	0.36	4.6	0.23	64	1.846	21	0.16	0.727	93
	A.6.13	wall b	0.43	5.0	0.17	70	1.883	17	0.24	0.279	95
	A.6.13	wall c	0.3	4.4	0.19	70	1.357	19	0.14	0.307	96
average	***A.6.13***	***wall***	***0.4***	***4.7***	***0.19***	***68***	***1.7***	***19***	***0.18***	***0.44***	***95***
standard deviation			*0.1*	*0.3*	*0.03*	*4*	*0.29*	*2*	*0.05*	*0.25*	
	A.6.5	wall a	0.28	3.4	0.16	66	0.705	25	0.08	0.627	96
	A.6.5	wall b	0.32	3.3	0.1	65	0.834	26	0.12	0.49	97
	A.6.5	wall c	0.26	3.4	0.12	66	0.676	24	0.12	0.432	95
average	***A.6.5***	***wall***	***0.3***	***3.4***	***0.12***	***66***	***0.74***	***25***	***0.11***	***0.52***	***96***
standard deviation			*0*	*0.1*	*0.03*	*0*	*0.08*	*1*	*0.02*	*0.1*	

Black glaze	sample #		CaO	K_2O	Na_2O	SiO_2	FeO	Al_2O_3	MgO	TiO_2	Totals
	203	black glaze	10.5	3.3	0.32	55	1.376	21	1.81	0.413	93
	546	black glaze	15	5.8	0.29	50	1.014	20	1.08	0.375	93
	546	black glaze light area	27.7	2.3	0.09	39	1.011	16	1.6	0.311	88
	546	black glaze dark area	17.8	6.1	0.52	49	0.842	18	0.95	0.352	94
average	203 and 546		12.8	4.5	0.31	52	1.195	20	1.45	0.394	94

Lutting	sample #		CaO	K_2O	Na_2O	SiO_2	FeO	Al_2O_3	MgO	TiO_2	Totals
	double lid	lutting a	0.57	7.1	0.31	67	0.343	18	0.25	0.1	94
	double lid	lutting b	0.63	5.5	0.47	60	0.318	25	0.18	0.163	92
	double lid	lutting c	0.42	6.5	0.41	67	0.67	18	0.19	0.103	93
average	***double lid***	***lutting***	***0.5***	***6.4***	***0.4***	***65***	***0.44***	***20***	***0.2***	***0.12***	***93***
standard deviation			*0.1*	*0.8*	*0.08*	*4*	*0.2*	*4*	*0.04*	*0.04*	

Bases	***sample #***		***CaO***	***K_2O***	***Na_2O***	***SiO_2***	***FeO***	***Al_2O_3***	***MgO***	***TiO_2***	**Totals**
	G.8	base a	0.48	5.3	0.17	67	0.966	23	0.3	0.134	98
	G.8	base b	0.41	4.5	0.13	67	1.518	26	0.3	0.393	100
	G.8	base c	0.65	7.7	0.24	69	1.121	18	0.17	0	97
average	***G.8***	***base matrix***	***0.5***	***5.8***	***0.18***	***67***	***1.2***	***23***	***0.26***	***0.18***	***98***
standard deviation			*0.1*	*1.7*	*0.06*	*1*	*0.28*	*4*	*0.08*	*0.2*	
	203	base b	0.33	3.0	0.22	54	1.538	38	0.2	0.563	97
	203	base c	0.72	6.0	0.18	68	2.651	18	0.17	0.03	96
	203	base d	0.35	2.6	0.01	55	1.354	35	0.22	0.536	95
average	***203***	***base***	***0.5***	***3.9***	***0.14***	***59***	***1.85***	***30***	***0.2***	***0.38***	***96***
standard deviation			*0.2*	*1.9*	*0.11*	*8*	*0.7*	*10*	*0.03*	*0.3*	
unusual	203	base a	5.83	2.2	0.2	26	0.914	12	1	0.241	48
	202	base a	0.29	3.4	0.11	64	1.174	27	0.18	0.555	97
	202	base b	0.29	3.6	0.08	66	0.955	26	0.15	0.573	97
	202	base c	0.35	4.8	0.11	77	1.178	15	0.16	0.578	99
average	***202***	***base***	***0.3***	***4.0***	***0.1***	***69***	***1.1***	***23***	***0.16***	***0.57***	***98***
standard deviation			*0*	*0.8*	*0.02*	*7*	*0.13*	*7*	*0.02*	*0.01*	
glassy	546	base (needles) a	9.32	1.9	0.4	49	0.945	22	0.7	0.414	85
glassy	546	base b	11.4	1.4	0.3	53	1.501	24	1.3	0.402	94
	546	base c	0.24	3.4	0.05	64	0.668	29	0.11	0.657	97
average	***546***	***'nrepresentative bas***	***7***	***2.2***	***0.25***	***55***	***1.04***	***25***	***0.7***	***0.49***	***92***
standard deviation			*5.9*	*1.0*	*0.18*	*8*	*0.42*	*3*	*0.6*	*0.14*	
	546	one crystal	15.1	0.9	0.3	51	0.334	29	0.25	0.156	97

Pads	***sample #***		***CaO***	***K2O***	***Na2O***	***SiO2***	***FeO***	***Al2O3***	***MgO***	***TiO2***	**Totals**
	546	pad a	18	1.2	0.3	50	1.647	22	1.28	0.401	95
	546	pad b	0.19	2.8	0.1	60	0.565	33	0.07	0.423	97
	546	pad c	0.95	5.5	0.16	67	0.972	20	0.24	0.43	95
average	***546***	***pad***	***6.4***	***3.2***	***0.19***	***59***	***1.06***	***25***	***0.53***	***0.42***	***96***
standard deviation											
	G.8	pad a	12.6	1.5	0.22	55	2.086	22	1.07	0.34	95
	G.8	pad b	0.28	2.9	0.02	68	0.498	32	0.06	0.348	104
	G.8	pad c	13.5	1.6	0.29	57	1.211	22	0.95	0.387	97
average	***G.8***	***pad***	***8.8***	***2.0***	***0.18***	***60***	***1.27***	***25***	***0.69***	***0.36***	***98***
standard deviation			*7.4*	*0.8*	*0.14*	*7*	*0.8*	*5*	*0.55*	*0.03*	
	202	pad a	15.6	1.9	0.09	58	1.748	15	1.25	0.552	95
	202	pad b	7.99	3.5	0.27	61	1.388	20	0.7	0.376	95
	202	pad c	0.18	2.5	0.01	57	0.635	34	0.07	1.012	96
average	***202***	***pad***	***7.9***	***2.7***	***0.12***	***59***	***1.26***	***23***	***0.67***	***0.65***	***95***
standard deviation			*7.7*	*0.8*	*0.14*	*2*	*0.57*	*10*	*0.59*	*0.33*	
	203	pad a	7.75	3.1	0.4	57	1.316	22	1.2	0.503	94
	203	pad b	0.62	4.8	0.22	70	0.675	21	0.18	0.185	98
	203	pad c	16.6	0.7	0.17	52	1.015	21	1.83	0.511	93
average	***203***	***pad***	***8.3***	***2.9***	***0.26***	***60***	***1***	***21***	***1.07***	***0.4***	***95***
standard deviation			*8*	*2.0*	*0.12*	*9*	*0.32*	*1*	*0.84*	*0.19*	

Appendix E: Merv Crucible Slag

	sample		BaO	P_2O_5	CaO	K_2O	Na_2O	SiO_2	FeO	MnO	Al_2O_3	MgO	TiO_2	V_2O_5	SO_3	TOTAL
av oxide	#1	w/ crucible	0.75	0.04	20.5	2.0	0.2	45.4	0.9	**12.0**	13.5	1.8	0.46	*0.04*	0.3	98.0
av oxide	# 6		0.92	0.05	11.8	2.6	0.3	52.4	2.1	**10.9**	15.1	2.1	0.50	*0.07*	0.0	98.9
av oxide	# 18	w/crucible	0.80	0.00	9.2	3.5	0.2	51.6	2.5	**9.1**	17.3	1.4	0.49	*0.07*	0.0	96.1
av oxide	# 7		1.26	0.00	15.1	2.7	0.3	47.1	1.3	**12.8**	13.8	2.3	0.51	*0.08*	0.0	97.2
av oxide	# 11	slag only	1.22	0.01	14.8	2.6	0.3	47.6	1.5	**12.9**	14.2	2.3	0.48	*0.07*	0.1	98.1
av oxide	# 13	slag only	0.38	0.02	15.3	2.0	0.1	45.4	1.2	**17.6**	13.0	2.1	0.39	*0.06*	0.2	97.8
av oxide	# 10	slag only	0.89	0.00	10.4	3.3	0.2	52.0	2.1	**9.6**	17.3	1.7	0.51	*0.04*	0.0	97.9
average high mn group			*0.89*	*0.02*	*13.9*	*2.7*	*0.2*	*48.8*	*1.6*	***12.1***	*14.9*	*2.0*	*0.48*	*0.06*	*0.08*	*97.7*
av oxide	# 32	w/ crucible	0.09	0.01	18.7	3.2	0.2	48.8	0.6	**0.7**	17.3	2.7	0.47	*0.04*	0.0	93.0
av oxide	# A.3.8	w/ crucible?	0.08	0.07	13.6	6.4	0.1	52.2	0.3	**0.1**	16.7	3.3	0.41	*0.04*	**1.4**	94.6
av oxide	# 5	w/crucible	0.07	0.05	22.3	4.7	0.4	48.0	2.3	**2.0**	15.0	2.7	0.49	*0.06*	0.0	98.0
av oxide	# 19	w/crucible	0.10	0.02	22.3	4.0	0.3	46.5	1.0	**3.6**	14.0	3.4	0.55	*0.06*	0.0	96.0
av oxide	# 2	w/crucible	0.03	0.21	11.0	6.0	0.2	53.4	1.8	**0.1**	18.9	2.0	0.43	*0.06*	0.2	94.3
av oxide	# A3.7 (not A.3.7)		0.05	0.01	19.3	2.3	0.2	48.8	0.9	**1.6**	17.0	4.0	0.61	*0.07*	0.0	94.8
av oxide	# 17		0.12	0.00	16.6	3.5	0.2	50.5	1.5	**3.8**	15.2	2.9	0.55	*0.06*	0.0	95.0
av oxide	# 4	w/crucible	0.04	0.06	19.6	2.7	0.1	49.1	2.0	**3.7**	15.2	3.0	0.50	*0.05*	0.0	96.2
av oxide	# A.3.7		0.11	0.01	18.4	2.2	0.1	49.1	0.8	**1.6**	17.1	4.3	0.24	*0.05*	0.0	94.0
av oxide	# 14	slag only	0.11	0.03	21.1	3.6	0.2	45.6	1.2	**4.3**	14.2	3.5	0.48	*0.06*	0.0	94.4
av oxide	# 15	slag only	0.10	0.03	13.8	4.0	0.2	52.0	1.7	**2.7**	16.2	2.8	0.52	*0.07*	0.0	94.2
av oxide	# 12	slag only?	0.12	0.02	16.0	4.4	0.2	52.2	1.2	**1.3**	14.6	2.8	0.64	*0.05*	0.0	93.5
av oxide	# 16		0.14	0.08	16.3	5.2	0.4	53.2	1.6	**1.7**	16.3	2.3	0.57	*0.03*	0.0	97.8
average low Mn group			*0.09*	*0.05*	*17.6*	*4.0*	*0.2*	*50.0*	*1.3*	*2.1*	*16.0*	*3.1*	*0.50*	*0.05*	*0.1*	
average high Mn group			*0.89*	*0.02*	*13.9*	*2.7*	*0.2*	*48.8*	*1.6*	*12.1*	*14.9*	*2.0*	*0.48*	*0.06*	*0.1*	
Average Slag			***0.37***	***0.04***	***16.3***	***3.5***	***0.2***	***49.5***	***1.4***	***5.6***	***15.6***	***2.7***	***0.49***	***0.06***	***0.12***	

ODD samples			BaO	P_2O_5	CaO	K_2O	Na_2O	SiO_2	FeO	MnO	Al_2O_3	MgO	TiO_2	V_2O_5	SO_3	TOTAL
av oxide	# 8		0.0	0.0	13.1	3.3	0.3	37.7	3.3	**2.7**	16.6	2.2	0.5	0.1	0.0	79.9
av oxide	# 34	w/crucible	0.0	0.0	4.8	4.0	0.2	56.1	6.9	**1.9**	18.5	0.8	0.4	0.1	0.0	93.8

Appendix F: EPMA of Ore, Heated Ore and Smithing Hearth Bottom

sample	description	figure	FeO	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	MnO	BaO	P_2O_5	Cl	CuO	V_2O_5	PbO	TiO_2	Total
150	light grey A		**81.8**	1.0	0.3	1.9	0.0	0.0	0.0	0.0	0.7	0.0	0.1	0.0	0.0	0.0	0.2	0.0	*86.1*
150	light grey B		**81.0**	0.4	0.4	0.6	0.0	0.3	0.0	0.0	0.7	0.0	0.1	0.0	0.0	0.0	0.2	0.1	*83.6*
150	light grey C		**71.9**	2.1	0.6	0.6	0.0	0.2	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*75.9*
150	glassy top A		5.6	**51.4**	**11.5**	**18.4**	2.6	2.5	0.2	0.1	0.1	0.1	0.7	0.1	0.6	0.1	0.8	0.5	*95.3*
150	glassy top B		3.3	**54.1**	**11.9**	**14.2**	3.2	1.7	1.1	0.1	0.1	0.1	0.5	0.1	0.3	0.1	0.2	0.6	*91.3*
150	glassy top C		3.6	**48.4**	**13.4**	**12.1**	3.4	2.3	0.8	0.2	0.2	0.1	0.6	0.1	0.2	0.1	0.3	0.4	*86.1*
150	green slag		**13.1**	**35.5**	7.7	**15.9**	2.4	2.8	1.3	0.1	0.3	0.0	0.6	0.0	0.6	0.0	1.0	0.3	*81.4*
150	green slag A		6.4	**49.2**	**10.0**	**16.3**	3.7	2.7	0.0	0.1	0.2	0.1	0.9	0.1	1.6	0.1	2.3	0.3	*94.0*
150	green slag B		**15.8**	**42.0**	**8.4**	**17.2**	1.9	1.6	2.1	0.0	0.2	0.0	0.6	0.0	0.5	0.1	0.6	0.3	*91.1*
150	green slag C		**21.2**	**36.8**	**6.4**	**19.4**	0.9	1.1	2.0	0.0	0.5	0.0	0.5	0.0	0.5	0.1	0.6	0.3	*90.1*

sample	description	figure	FeO	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	MnO	BaO	P_2O_5	Cl	CuO	V_2O_5	PbO	TiO_2	Total
149	white area A		0.1	13.9	1.1	**53.5**	1.1	0.1	0.0	1.1	0.0	0.0	0.2	0.4	0.0	0.0	0.0	0.0	*71.5*
149	white area B	A	0.4	0.0	0.2	**63.7**	0.1	0.0	0.3	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	*65.1*
149	white area C		0.1	0.0	0.0	**62.5**	0.0	0.5	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	*63.4*
149	white area D		0.1	0.0	0.1	**59.7**	0.1	0.3	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	*60.6*
149	dark grey A		1.1	**32.7**	0.0	**63.4**	0.2	0.3	0.1	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	*98.5*
149	dark grey B	B	1.0	**32.0**	0.1	**64.2**	0.3	0.2	0.1	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	*98.8*
149	dark grey C		**8.4**	**30.6**	**37.2**	**25.4**	0.5	**4.9**	0.4	0.4	0.0	0.1	0.2	0.5	0.2	0.0	0.0	0.2	*108.9*
149	light grey A		**85.2**	0.0	0.0	1.4	0.0	0.6	**3.3**	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.1	0.2	*91.3*
149	light grey B		**71.3**	11.5	0.0	**15.2**	0.0	0.8	**2.3**	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.1	0.2	*102.2*
149	light grey C	C	**47.9**	19.9	1.5	**25.5**	0.0	0.6	0.4	0.1	0.3	0.0	0.4	0.0	0.0	0.0	0.1	0.2	*96.8*
149	light grey D		**85.7**	0.0	0.5	0.6	0.0	0.3	**3.4**	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.1	0.1	*91.4*

Appendix F: EPMA of Ore, Heated Ore and Smithing Hearth Bottom

sample	description	figure	FeO	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	MnO	BaO	P_2O_5	Cl	CuO	V_2O_5	PbO	TiO_2	Total
161	Bright A	A	**88.1**	0.0	0.0	**6.5**	0.0	0.0	0.6	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*96.0*
161	Bright B		**87.5**	0.0	0.0	**6.7**	0.0	0.0	0.5	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*95.4*
161	Bright C		**86.4**	0.0	0.0	**7.0**	0.0	0.0	0.5	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*94.7*
161	Mid grey A		**70.6**	0.0	0.0	0.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.1	0.0	*71.6*
161	Mid grey B		**69.6**	0.0	0.0	0.3	0.0	0.0	0.1	0.3	0.0	0.0	0.1	0.3	0.1	0.0	0.1	0.0	*70.8*
161	Mid grey C	B	**72.2**	0.0	0.0	0.2	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	*73.2*
161	Dark Hole A	C	**62.0**	**10.0**	4.6	2.2	0.0	0.2	0.2	0.3	0.0	0.0	0.4	0.4	0.6	0.0	0.1	0.0	*80.8*
161	Dark Hole B		**67.0**	2.2	2.8	1.0	0.0	0.1	0.3	0.5	0.0	0.0	0.2	0.4	1.0	0.0	0.1	0.0	*75.6*
161	Dark Hole C	D	0.4	0.0	0.0	**47.2**	0.0	0.0	0.0	**50.7**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*98.4*

sample	description	figure	FeO	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	MnO	BaO	P_2O_5	Cl	CuO	V_2O_5	PbO	TiO_2	Total
46	light A		**84.3**	0.0	0.1	0.2	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.2	0.0	*84.9*
46	light B		**60.5**	19.8	3.3	11.3	0.0	0.9	0.1	0.8	0.1	0.0	0.3	0.4	0.0	0.0	0.1	0.0	*97.5*
46	light C	A	**85.3**	0.0	0.5	0.1	0.0	0.0	0.5	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*86.8*
46	Dark spot A	B	0.5	10.4	6.6	**38.5**	0.2	0.1	0.0	**16.6**	0.0	0.0	0.1	0.6	0.0	0.0	0.0	0.0	*73.7*
46	Dark spot B		0.7	12.6	6.2	**29.0**	0.2	0.6	0.0	**10.6**	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	*60.2*
46	Dark spot C		3.9	27.4	0.0	**32.0**	0.6	0.6	0.1	1.2	0.0	0.0	**1.5**	0.6	0.0	0.0	0.0	0.0	*67.9*
46	top A	D	11.8	**54.8**	**9.9**	**12.2**	3.3	1.4	0.3	0.1	0.1	0.1	1.1	0.1	0.0	0.0	0.0	0.3	*95.5*
46	top B		**21.2**	**44.4**	4.2	**20.9**	0.3	0.3	2.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.3	*93.9*
46	top C		**32.0**	**39.0**	7.1	**10.3**	2.0	1.5	0.6	0.1	0.1	0.1	**1.4**	0.1	0.0	0.0	0.1	0.2	*94.5*
46	Further Up A		6.7	**52.4**	5.8	**16.9**	2.0	0.6	4.0	0.0	0.1	0.0	0.2	0.0	0.0	0.1	0.1	0.4	*89.2*
46	Further Up B		7.6	**47.1**	**8.6**	**20.1**	1.5	1.2	**3.9**	0.0	0.1	0.0	0.7	0.0	0.0	0.1	0.1	0.6	*91.5*
46	Further Up C		4.7	**58.0**	11.3	**16.3**	2.8	1.9	**3.9**	0.1	0.1	0.0	**3.8**	0.1	0.0	0.1	0.0	0.4	*103.5*
46	mid section A		**84.5**	0.0	0.0	0.5	0.0	0.0	0.3	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*86.1*
46	mid section B		**81.8**	0.0	0.0	0.9	0.0	0.0	0.1	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*83.3*
46	mid section C		**76.2**	0.0	0.6	1.8	0.0	0.1	1.8	0.1	1.2	0.0	0.0	0.0	0.0	0.0	0.2	0.0	*81.9*
46	mid grey A		1.1	**32.4**	0.0	**63.5**	0.4	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	*98.2*
46	mid grey B	C	1.3	**32.1**	0.0	**62.4**	0.3	0.0	0.0	0.0	0.0	0.0	**1.1**	0.0	0.0	0.0	0.0	0.0	*97.2*
46	mid grey C		1.2	**32.5**	0.0	**62.7**	0.2	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	*97.4*

Appendix F: EPMA of Ore, Heated Ore and Smithing Hearth Bottom

sample	description	figure	FeO	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	MnO	BaO	P_2O_5	Cl	CuO	V_2O_5	PbO	TiO_2	Total
3153 F			7.4	0.1	0.0	**50.8**	0.6	0.1	0.0	1.0	0.1	0.1	0.6	0.4	0.0	0.0	0.1	0.0	*61.2*
3153 F	white area?		**40.7**	**7.9**	0.0	**17.6**	0.0	0.4	**2.0**	0.3	0.2	0.0	0.1	0.0	0.2	0.0	0.1	0.0	*69.7*
3153F	slag?		**51.4**	**29.5**	0.0	**3.6**	2.1	1.0	**3.1**	0.2	0.2	0.0	0.3	0.6	0.7	0.0	0.1	0.0	*92.8*
3153 F			**60.2**	**5.1**	0.0	**1.3**	0.0	0.0	1.0	0.4	0.0	0.0	0.6	**3.1**	**1.2**	0.0	0.1	0.0	*73.1*
3153 F			**52.6**	**6.1**	0.0	**7.1**	0.0	0.1	1.3	0.5	0.0	0.0	0.5	**2.5**	**1.1**	0.0	0.2	0.0	*72.1*
3153 F		A	2.0	0.6	0.0	**27.9**	0.8	0.2	**5.5**	0.2	0.0	0.0	0.2	0.1	0.6	0.0	0.0	0.0	*38.0*
3153 F	bright A		**94.3**	0.0	0.1	1.5	0.0	0.0	0.7	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.2	0.0	*97.3*
3153 F	bright B	B	**92.9**	0.0	0.2	1.5	0.0	0.0	0.7	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*95.7*
3153 F	bright C		**94.3**	0.0	0.0	1.4	0.0	0.0	0.7	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.2	0.0	*97.1*
3153 F			**30.8**	**23.0**	0.5	**34.4**	0.6	0.2	0.2	**4.5**	0.1	0.2	0.1	0.0	3.9	0.0	0.1	0.0	*98.5*
3153 F			**73.5**	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.0	*74.1*
3153 F			**65.1**	0.4	0.0	0.5	0.0	0.3	0.1	0.1	0.0	0.0	0.1	**2.5**	0.8	0.0	0.1	0.0	*70.0*
3153 F			**17.3**	**25.8**	**4.0**	**48.5**	0.7	0.1	0.3	**2.0**	0.2	0.2	0.9	0.0	0.2	0.0	0.0	0.1	*100.3*
3153 F	light A		**90.4**	0.0	0.1	**3.0**	0.0	0.0	0.6	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*94.5*
3153 F	light B	C	**89.2**	0.0	0.3	**3.1**	0.0	0.0	0.5	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*93.5*
3153 F	light C		**90.6**	0.0	0.0	**2.9**	0.0	0.0	0.8	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*94.7*
3153 F	slag A		2.1	**32.3**	0.0	**63.3**	0.2	0.0	0.0	0.1	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	*98.6*
3153 F	slag B	D	1.6	**32.4**	0.0	**63.8**	0.4	0.1	0.0	0.1	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	*99.6*
3153 F	slag C		**5.8**	**29.1**	0.0	**58.7**	1.3	0.4	0.0	0.0	0.0	0.0	**5.3**	0.0	0.0	0.0	0.1	0.0	*100.7*
3153 F			0.9	**32.1**	0.6	**35.4**	0.3	0.3	0.0	0.6	0.0	0.0	0.4	1.4	0.6	0.0	0.0	0.0	*72.5*
3153 F			1.7	**35.7**	0.7	**35.3**	0.2	0.1	0.0	0.5	0.0	0.0	0.3	0.6	0.2	0.0	0.0	0.0	*75.2*
3153 F			1.4	**19.5**	2.1	**40.4**	0.2	0.0	0.0	18.7	0.0	0.0	0.2	0.5	0.1	0.0	0.0	0.0	*83.0*

sample	description	figure	FeO	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	MnO	BaO	P_2O_5	Cl	CuO	V_2O_5	PbO	TiO_2	Total
45			88.7	0.0	0.3	0.1	0.0	0.2	0.8	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	*90.4*
45			60.3	23.7	0.0	19.8	0.0	0.2	1.4	0.0	0.1	0.0	0.5	0.0	0.0	0.0	0.1	0.1	*106.3*
45			92.3	0.0	0.2	0.3	0.0	0.1	0.7	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.2	0.1	*94.0*
45			26.2	31.2	0.0	35.3	0.0	0.2	1.3	0.0	0.1	0.0	0.9	0.0	0.0	0.0	0.0	0.0	*95.2*

Appendix F: EPMA of Ore, Heated Ore and Smithing Hearth Bottom

sample	description	figure	FeO	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	MnO	BaO	P_2O_5	Cl	CuO	V_2O_5	PbO	TiO_2	Total
3153 K	angular A	A	4.8	**30.6**	**16.6**	**39.2**	0.2	0.0	**2.1**	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*93.8*
3153 K	angular B		6.0	**32.4**	**13.4**	**38.6**	0.6	0.1	**2.1**	0.0	0.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	*93.8*
3153 K	angular C		**11.0**	**32.7**	**11.5**	**32.0**	1.5	0.1	**1.5**	0.3	**1.7**	0.2	1.6	0.0	0.0	0.0	0.0	0.3	*94.5*
3153 K	white dendrite /	B	**88.7**	0.0	0.4	0.5	0.0	0.0	**1.5**	0.0	**2.1**	0.0	0.0	0.0	0.0	0.0	0.1	0.3	*93.7*
3153 K	white dendrite B		10.1	39.3	13.3	36.3	0.5	0.2	**2.4**	0.0	0.3	0.0	0.1	0.0	0.0	0.0	0.0	0.0	*102.4*
3153 K	white dendrite C		87.0	0.0	0.4	0.5	0.0	0.0	**1.6**	0.0	2.6	0.0	0.0	0.0	0.0	0.1	0.1	0.3	*92.6*
3153 K	matrix A		**79.4**	3.0	1.9	5.1	0.0	0.0	**2.2**	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	*94.0*
3153 K	Matrix B		**40.3**	**21.5**	**13.5**	**23.7**	0.0	0.0	**2.2**	0.0	0.5	0.0	0.1	0.0	0.0	0.0	0.1	0.1	*101.9*
3153 K	Matrix C		**9.3**	**35.5**	**10.7**	**35.9**	0.9	0.2	**2.5**	0.0	0.7	0.0	0.2	0.0	0.0	0.0	0.0	0.0	*95.9*
3153 K	A	C	**89.1**	0.0	0.3	1.0	0.0	0.0	**2.1**	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.2	0.1	*93.6*
3153 K	B		**22.2**	**24.6**	**13.7**	**32.4**	0.0	0.0	**1.7**	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*94.8*
3153 K	C		**7.5**	**33.6**	**12.5**	**37.9**	0.4	0.1	**2.4**	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*94.7*
3153 K	A	D	0.2	**5.0**	**5.3**	**36.7**	0.0	0.0	0.0	**20.8**	0.1	0.0	0.2	0.2	0.0	0.0	0.0	0.0	*68.4*
3153 K	B		0.2	**4.2**	**4.1**	**29.5**	0.0	0.0	0.0	**15.9**	0.1	0.0	0.2	0.2	0.0	0.0	0.0	0.0	*54.3*
3153 K	C		0.2	**6.0**	**5.6**	**32.1**	0.0	0.0	0.0	**17.9**	0.1	0.0	0.3	0.2	0.0	0.0	0.0	0.0	*62.2*
3153 K	A	E	17.8	**32.3**	**12.1**	**23.8**	**2.2**	0.0	1.3	0.3	3.5	0.3	1.1	0.0	0.0	0.1	0.0	0.4	*95.4*
3153 K	B		14.6	**28.2**	**10.8**	**25.4**	**2.3**	0.0	1.0	0.3	3.6	0.4	0.9	0.0	0.1	0.1	0.0	0.4	*87.9*
3153 K	C		13.8	**34.1**	**13.2**	**25.5**	**2.0**	0.1	1.4	0.2	3.7	0.3	0.8	0.0	0.0	0.1	0.0	0.4	*95.6*
3153 K	A	F	0.9	**51.5**	**21.9**	**6.6**	**3.8**	0.3	0.6	1.0	0.3	0.0	0.1	0.0	0.0	0.1	0.0	0.4	*87.4*
3153 K	B		1.6	**66.6**	**18.4**	0.2	**1.5**	**8.4**	0.4	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	*97.2*
3153 K	C		2.3	**50.1**	**17.1**	1.2	**7.8**	0.4	0.7	0.0	0.0	0.3	0.0	0.0	0.0	0.1	0.0	0.8	*80.9*
3153 K	Matrix A	G	**69.8**	0.0	0.0	0.3	0.0	0.1	0.0	0.3	0.0	0.0	0.1	0.4	0.1	0.0	0.1	0.0	*71.1*
3153 K	Matrix B		**70.5**	0.8	0.0	0.6	0.0	0.0	0.1	0.2	0.1	0.0	0.1	0.6	0.0	0.0	0.1	0.0	*73.1*
3153 K	Matrix C		**71.2**	0.0	0.0	0.3	0.0	0.0	0.2	0.3	0.0	0.0	0.1	0.2	0.2	0.0	0.1	0.0	*72.5*
3153 K	light gray A		**78.0**	0.0	0.0	**6.5**	0.0	0.0	**4.2**	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*89.5*
3153 K	light gray B		**41.7**	**9.5**	0.1	**17.3**	0.0	0.0	**3.8**	**2.2**	0.2	0.0	0.9	0.1	0.8	0.0	0.1	0.0	*76.6*
3153 K	light gray C		**30.2**	**15.0**	0.3	**27.5**	0.0	0.2	0.1	1.3	0.1	0.0	0.2	0.3	0.2	0.0	0.1	0.0	*75.5*
3153 K	darker grey A		**44.4**	0.0	**4.5**	**42.8**	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	*92.0*
3153 K	darker grey B		**73.2**	0.0	0.0	**10.9**	0.0	0.0	**5.6**	0.3	0.8	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*90.8*
3153 K	darker grey C		**47.5**	0.0	1.5	**43.0**	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	*92.3*
3153 K			0.1	**101.9**	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*102.2*

3153 K *continued*

sample	description	figure	FeO	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	MnO	BaO	P_2O_5	Cl	CuO	V_2O_5	PbO	TiO_2	Total
3153 K	Matrix A		2.0	0.0	0.0	**52.1**	0.2	0.3	**2.1**	**1.4**	0.1	0.0	0.3	0.0	0.2	0.0	0.0	0.0	*58.6*
3153 K	Matrix B		0.1	0.0	0.4	**52.5**	0.2	0.2	**2.6**	0.8	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	*57.2*
3153 K	Matrix C		0.2	0.0	0.0	**63.1**	0.8	0.3	0.0	0.4	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	*64.8*
3153 K	Bright A		**56.3**	**6.3**	0.2	**4.7**	0.0	0.2	**1.0**	0.4	0.1	0.0	0.7	0.1	0.5	0.0	0.1	0.0	*70.6*
3153 K	Bright B		**47.6**	**12.7**	**2.0**	**5.3**	0.6	0.0	**1.0**	0.5	0.1	0.0	0.5	0.1	0.5	0.0	0.1	0.1	*71.1*
3153 K	Bright C		**38.9**	**8.8**	**1.4**	**10.2**	0.2	0.0	**1.5**	0.4	0.1	0.0	0.5	0.1	0.6	0.0	0.1	0.1	*63.0*
3153 K	A		**41.9**	0.0	**6.6**	**43.7**	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.4	*92.9*
3153 K	B		**41.3**	0.0	**7.0**	**43.9**	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.5	*93.1*
3153 K	C		**42.2**	0.4	**5.8**	**43.3**	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.1	*92.0*
3153 K	A		0.1	0.0	0.0	**42.7**	0.0	0.0	0.0	**46.2**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*89.0*
3153 K	B		0.3	0.6	0.6	**58.6**	0.8	0.1	0.0	**1.0**	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	*62.4*
3153 K	C	I	0.8	**48.4**	0.1	**29.2**	1.2	0.1	0.0	0.6	0.0	0.0	2.9	0.1	0.0	0.0	0.0	0.0	*83.4*
3153 K		J	**28.1**	0.0	**19.1**	**47.5**	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	1.0	*95.8*
3153 K		K	0.9	**32.2**	0.1	**62.9**	0.8	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	*98.7*
3153 K			0.8	**30.7**	0.1	**62.3**	**1.1**	0.0	0.0	0.1	0.0	0.0	2.3	0.0	0.1	0.0	0.0	0.0	*97.6*
3153 K			1.2	**31.3**	0.3	**61.5**	0.7	0.1	0.0	0.1	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	*96.9*
3153 K			2.1	**33.1**	0.6	**22.6**	0.7	0.2	0.2	0.5	0.0	0.0	1.9	0.0	0.1	0.0	0.0	0.0	*62.0*
3153 K			**80.0**	0.0	0.0	**2.8**	0.0	0.0	6.5	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*90.1*
3153 K		L	**80.4**	0.0	0.0	**4.1**	0.0	0.0	5.9	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.1	0.0	*91.2*
3153 K			0.9	31.5	0.0	**62.0**	0.7	0.0	0.4	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	*96.7*
3153 K			**35.1**	0.0	**12.8**	**44.9**	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.3	*93.2*

Appendic G: EPMA of Merv Iron and Steel

UNK No.	*ID*	Fe	P	Cu	S	Mn		Total
4	*16*	96.1	0.25	0.15	0	0		**96.6**
5	*16*	95.3	0.23	0.14	0	0		**95.8**
6	*16*	94.4	0.27	0.13	0	0		**94.8**
7	*16 prill 2*	95.1	0.27	0.11	0	0		**95.6**
8	*16 prill 2*	95.5	0.24	0.16	0.022	0		**96.0**
average	***16***	***95.3***	***0.25***	***0.14***	***0***	***0***		***95.66***

UNK No.	*ID*	Fe	P	Cu	S	Mn		Total
9	*12*	94.6	0.09	0.15	0.131	0		**95.0**
10	*12*	98.4	0.09	0.16	0	0		**98.9**
11	*12*	95.1	0.11	0.15	0	0		**95.5**
12	*12*	94.1	0.09	0.19	0	0		**94.8**
average	***12***	***95.6***	***0.09***	***0.16***	***0.03***	***0***		***95.85***

UNK No.	*ID*	Fe	P	Cu	S	Mn		Total
1	*Merv bulat*	99.5	0.02	0.10	0	0		**99.7**
2	*Merv bulat*	99.5	0.02	0.11	0	0		**99.7**
3	*Merv bulat*	99.9	0.02	0.08	0	0		**100.1**
4	*Merv bulat*	101	0	0.04	0	0		**101.5**
average	***Merv bulat***	***100***	***0.02***	***0.08***	***0***	***0***		***100.2***

UNK No.	*ID*	Fe	P	Cu	S	Mn		Total
8	*10*	98.8	0	0.17	0	0		**99.4**
9	*10*	96.7	0	0.18	0	0.12		**97.3**
10	*10*	95.8	0	0.15	0	0.11		**96.3**
11	*10 prill 2*	95.9	0	0.14	0	0.13		**96.4**
12	*10 prill 2*	95.3	0.16	0.17	0	0.11		**95.9**
13	*10 prill 2*	93.8	0	0.15	0	0.14		**94.3**
average	***10***	**96**	**0.03**	**0.16**	**0**	**0.1**		**96.3**

UNK No.	*ID*	Fe	P	Cu	S	Mn	Ca	Total
14	*8*	97.8	0.03	0.29	0	0		**98.2**
15	*8*	95.1	0.02	0.30	0	0		**95.6**
16	*8*	97.6	0.02	0.30	0	0		**98.0**
17	*8*	95.8	0.05	0.28	0	0		**96.2**
average	***8***	***96.6***	***0.03***	***0.29***	***0***	***0***		***96.9***

UNK No.	*ID*	Fe	P	Cu	S	Mn		Total
18	*8*	95.1	0.02	0.28	0	0		**95.5**
19	*8*	96.6	0.03	0.31	0	0		**97.0**

different run

UNK No.		Fe	P	Cu	S	Mn	Ca	Total
2	*8*	95.7	0.06	0.25	0	0.05	0.02	**96.1**
3	*8*	94	0.06	0.27	0	0.04	0.02	**94.4**
4	*8*	93.9	0.09	0.26	0	0.06	0.08	**94.4**

Appendic G: EPMA of Merv Iron and Steel

UNK No.	*ID*	Fe	P	Cu	S	Mn	Total
2	*13*	91.2	0.1	0.33	0	0.26	**92.2**
3	*13*	96.3	0.08	0.32	0	0.3	**97.2**
4	*13*	96.8	0.06	0.31	0	0.31	**97.7**
5	*13*	97.0	0.12	0.32	0	0.33	**98.0**
6	*13*	90.1	0.08	0.29	0	0.32	**91.1**
7	*13*	91.4	0.26	0.33	0	0.25	**92.5**
average	***13***	***93.8***	***0.1***	***0.32***	***0.0***	***0.3***	***94.5***

UNK No.	*ID*	Fe	P	Cu	S	Mn	Total
line scan 1	*19*	94.0	0.07	0.09	0	0.14	**94.3**
2	*19*	93.0	0	0.09	0	0.19	**93.3**
3	*19*	95.0	0	0.09	0	0.14	**95.2**
4	*19*	94.0	0	0.08	0	0.15	**94.2**
5	*19*	93.0	0	0.09	0	0.16	**93.3**
6	*19*	95.0	0	0.05	0.1	0.16	**95.3**
7	*19*	95.0	0	0.1	0	0.16	**95.3**
average	***19***	***94.1***	***0.0***	***0.1***	***0.0***	***0.2***	***94.4***

UNK No.	*ID*	Fe	P	Cu	S	Mn	Total
4	*34*	92.0	0.05	0.1	0	0	**92.2**
5	*34*	95.0	0.1	0.1	0	0	**95.2**
6	*34*	95.0	0.07	0.1	0	0	**95.2**
7	*34*	95.0	0.07	0.1	0	0	**95.2**
average	***34***	***94.3***	***0.1***	***0.1***	***0.0***	***0.0***	***94.4***

UNK No.	*ID*	Fe	P	Cu	S	Mn	Ca	Total
8	*7*	94.0	0.06	0.3	0	0.06		**94.4**
9	*7*	95.0	0.06	0.3	0.1	0.06		**95.5**
10	*7*	92.0	0.05	0.3	0	0.07		**92.4**
11	*7*	95.0	0.05	0.2	0	0.1	***0.04***	**95.4**
average	***7***	***94.0***	***0.1***	***0.3***	***0.0***	***0.1***		***94.4***

UNK No.	*ID*	Fe	P	Cu	S	Mn	Ca	Total
12	*11*	93.0	0	0.3	0	0.08		**93.4**
13	*11*	96.0	0.05	0.3	0	0.09		**96.4**
14	*11*	96.0	0	0.2	0	0.09		**96.3**
15	*11 prill 2*	96.0	0	0.3	0	0.09	**0.02**	**96.4**
average	***11***	***95.0***	***0.0***	***0.3***	***0.0***	***0.1***		***95.4***

Points at 2 micron intervals	Fe	Si	Cu	Ni	P	Mn	S	V	Total
1	97	0	0.05	0	0.01	0.06	0.02	0.01	96.79
2	98	0	0.05	0	0.04	0.1	0.01	0.02	98.57
3	97	0	0.17	0	0	0.08	0.01	0.01	97.18
4	96	0	0.15	0	0.05	0.04	0.01	0.01	96.12
5	97	0	0.1	0.1	0.06	0.03	0.02	0.01	97.37
6	97	0	0.07	0	0.02	0.04	0	0	96.98
7	95	0	0.07	0	0.04	0.06	0.02	0	95.51
8	97	0	0.09	0	0.03	0.05	0.02	0.01	97.08
9	98	0	0.01	0	0	0.1	0.04	0.01	97.83
10	96	0	0.06	0	0.05	0.06	0.01	0.01	96.66
11	96	0	0.11	0	0.05	0.08	0	0.02	96.49
12	94	0	0.12	0	0.01	0.07	0	0	94.62
13	95	0	0.12	0	0.04	0.12	0	0	95.1
14	98	0	0.12	0	0.03	0.08	0	0.01	97.83
15	97	0	0.12	0	0.06	0.04	0.02	0	96.75
16	97	0	0.11	0	0.02	0.1	0.02	0.03	97.13
17	97	0	0.08	0	0.02	0.12	0.04	0	97.4
18	97	0	0.1	0	0.06	0.01	0.01	0	97.16
19	96	0	0.12	0	0.02	0.12	0.03	0.01	96.67
20	97	0	0.14	0	0.01	0.06	0.04	0	96.83
21	98	0	0.1	0	0.05	0.09	0.02	0.01	98.25
22	97	0	0.09	0	0.01	0.12	0	0	97.71
23	98	0	0.16	0	0	0.05	0	0.02	98.72
24	96	0	0.12	0	0	0.04	0	0.01	96.62
25	97	0	0.06	0	0.03	0.03	0	0.01	97.17
26	98	0	0.05	0	0.02	0.05	0	0	98.13
27	97	0	0.11	0	0.07	0.05	0	0	97.54
28	98	0	0.04	0	0	0.02	0	0.01	97.92
29	99	0	0.14	0	0	0.02	0	0.01	99.23
30	97	0	0.11	0	0.03	0.07	0	0.03	97.24
31	98	0	0.1	0.1	0.03	0.07	0	0.04	98.72
32	97	0	0.05	0	0.04	0	0.02	0.01	96.87
33	97	0	0.15	0	0.05	0.04	0	0	97.62
34	93	0	0.14	0	0	0.07	0.01	0.02	93.11
35	98	0	0.11	0	0.05	0.1	0	0.01	98.16
36	97	0	0.11	0	0.08	0.1	0	0.01	97.21
37	95	0	0.1	0	0.04	0.14	0.02	0.01	95.59
38	98	0	0.12	0	0.06	0.02	0	0.02	98.16
39	97	0	0.05	0	0.02	0.04	0.02	0.01	97.65
40	97	0	0.11	0	0.04	0.08	0	0.01	97.28
41	98	0	0.09	0	0.05	0.05	0	0.01	98.19
42	98	0	0.09	0	0.02	0.07	0	0	98.5
43	98	0	0.06	0	0.04	0.06	0	0	98.19
44	98	0	0.11	0	0.03	0.04	0	0.02	98.69
45	98	0	0.05	0	0	0.03	0.02	0.01	98.15
46	93	0	0.19	0	0.03	0.04	0.17	0	93.42
47	97	0	0.1	0	0.01	0.03	0.01	0	96.69
48	97	0	0.1	0	0.04	0.09	0.05	0.03	97.35
49	97	0	0.07	0	0.06	0.05	0.02	0.02	97.27
50	98	0	0.08	0	0.02	0.02	0	0.05	98.21

	Fe	Si	Cu	Ni	P	Mn	S	V	Total
51	98	0	0.07	0	0.06	0.04	0.02	0	98.16
52	98	0	0.05	0	0.01	0.07	0.02	0.03	98.08
53	96	0	0.1	0	0.04	0.04	0	0.02	96.55
54	97	0	0.13	0	0.04	0.02	0	0	97.13
55	98	0	0.16	0	0.02	0.06	0	0.02	98.75
56	94	0	0.1	0	0	0.06	0.02	0.01	94.12
57	97	0	0.14	0	0	0.05	0.02	0.01	97.14
58	97	0	0.13	0	0.04	0.05	0.01	0.01	97.12
59	97	0	0.08	0	0.06	0.04	0	0.02	96.94
60	98	0	0.09	0	0.02	0.06	0.02	0.02	98.18
61	97	0	0.11	0	0.03	0.07	0.01	0.01	96.89
62	97	0	0.09	0	0.01	0.06	0.01	0.01	96.87
63	99	0	0.07	0	0.03	0.15	0.07	0.03	99.13
64	99	0	0.08	0	0.03	0.08	0.01	0	99.07
65	98	0	0.16	0	0.02	0.15	0	0.02	97.97
66	98	0	0.11	0	0.06	0.07	0.01	0.01	98.44
67	97	0	0.13	0	0.04	0.04	0	0	97.66
68	97	0	0.1	0	0	0.08	0.37	0.03	97.69
69	95	0	0.07	0	0.06	0.08	0	0.02	95.48
70	97	0	0.15	0	0.05	0.11	0.07	0.01	97.23
71	97	0	0.07	0	0.07	0.1	0	0.01	97.27
72	97	0	0.13	0	0.04	0.08	0	0.02	97.62
73	97	0	0.11	0	0.07	0.05	0.03	0	96.89
74	97	0	0.06	0	0.05	0.05	0	0.02	97.26
75	98	0	0.11	0	0.05	0.08	0	0.01	97.93
76	98	0	0.12	0	0	0.08	0.01	0.01	97.89
77	98	0	0.1	0	0	0.08	0.02	0	98.2
78	97	0	0.08	0	0.04	0.1	0.01	0.01	96.85
79	96	0	0.13	0	0.04	0.07	0	0.01	96.32
80	98	0	0.14	0	0.01	0.06	0.03	0.02	97.91
81	96	0	0.18	0	0.04	0.1	0	0.02	95.93
82	97	0	0.1	0	0.04	0.03	0.05	0	97.09
83	96	0	0.15	0	0	0.11	0.02	0.02	96.82
84	97	0	0.11	0	0.01	0.08	0.12	0	97.18
85	97	0	0.09	0	0	0.08	0.02	0.01	97.21
86	98	0	0.1	0	0	0.07	0.01	0.01	97.8
87	98	0	0.08	0	0	0.06	0.01	0.01	97.67
88	96	0	0.11	0	0.03	0.09	0.02	0	96.13
89	95	0	0.16	0	0.07	0.04	0	0.02	94.92
90	96	0	0.06	0	0.02	0.13	0.07	0.01	96.11
91	97	0	0.1	0	0.01	0.09	0	0.01	97.52
92	96	0	0.09	0	0	0.1	0.02	0.01	96.44
93	98	0	0.05	0	0.05	0.03	0	0.01	98.34
94	96	0	0.11	0	0.01	0.07	0	0.01	96.26
95	97	0	0.12	0	0.01	0.1	0.02	0	97.12
96	97	0	0.12	0	0.04	0.03	0	0	97.12
97	97	0	0.1	0	0	0.09	0.01	0.02	97.38
98	97	0	0.11	0	0	0.05	0	0.01	96.83
99	97	0	0.07	0	0.01	0.05	0	0.02	97.03
100	98	0	0.07	0	0.04	0.07	0	0.01	97.76

	Fe	Si	Cu	Ni	P	Mn	S	V	Total
101	96	0	0.14	0	0	0.07	0	0	95.93
102	97	0	0.05	0	0	0.05	0.04	0.03	97.24
103	98	0	0.12	0	0	0.07	0	0	97.91
104	96	0	0.12	0	0.01	0.05	0	0	96.44
105	97	0	0.06	0	0.01	0	0.01	0.02	97.14
106	97	0	0.11	0.1	0.02	0.04	0	0.02	97.51
107	96	0	0.1	0	0.05	0	0	0.03	96.29
108	98	0	0.11	0.1	0.01	0.08	0	0	97.9
109	97	0	0.09	0	0.01	0.03	0	0	96.67
110	97	0	0.14	0	0.03	0.08	0	0.02	97.64
111	97	0	0.09	0	0.01	0	0	0.01	97.31
112	97	0	0.1	0	0	0.06	0	0.01	97.67
113	97	0	0.13	0	0.01	0.04	0.01	0	97.55
114	98	0	0.07	0	0.03	0.14	0	0.03	97.95
115	98	0	0.04	0	0.02	0.02	0	0.04	98.3
116	98	0	0.09	0	0.01	0.1	0.01	0.01	98.08
117	99	0	0.12	0.1	0.02	0.09	0.01	0.01	99.34
118	99	0	0.1	0	0	0.03	0.03	0	98.72
119	100	0	0.09	0	0.01	0.03	0.01	0.03	99.82
120	100	0	0.14	0	0	0.15	0.01	0.03	100.1
121	99	0	0.1	0	0.02	0.06	0.05	0.01	99.15
122	99	0	0.06	0	0	0.07	0.07	0.01	99.58
123	98	0	0.16	0	0.01	0.07	0.01	0.03	98.04
124	97	0	0.19	0	0.04	0	0.02	0.01	97.65
125	98	0	0.12	0	0	0.09	0.13	0.01	97.92
126	97	0	0.08	0	0.01	0.11	0.02	0.02	97.02
127	96	0	0.08	0	0.03	0.07	0	0	96.68
128	97	0	0.14	0	0.05	0.05	0	0.01	97.64
129	93	0	0.1	0	0.03	0.07	0	0.02	93.54
130	90	0	0.15	0	0.04	0.05	0	0	90.68
131	97	0	0.16	0	0.02	0.07	0.02	0.01	97.01
132	97	0	0.14	0	0.06	0.06	0	0.01	97.15
133	98	0	0.13	0	0.02	0.13	0.02	0.03	98.2
134	98	0	0.08	0	0.03	0.1	0	0.02	98.07
135	96	0	0.05	0	0	0.08	0.03	0.01	96.52
136	95	0	0.17	0	0	0.05	0	0.01	95.51
137	96	0	0.1	0	0.05	0.11	0.01	0	96.27
138	93	0	0.1	0	0.03	0.05	0.01	0.02	93.13
139	95	0	0.02	0	0.05	0.08	0	0.02	94.81
140	96	0	0.07	0	0.02	0.04	0	0	96.2
141	96	0	0.16	0	0.07	0.08	0.02	0	96.07
142	97	0	0.12	0	0.01	0.07	0.02	0.01	97.39
143	96	0	0.09	0	0.05	0.04	0.02	0	95.95
144	97	0	0.13	0	0.02	0.05	0	0.01	97.29
145	97	0	0.06	0	0.1	0.07	0	0.02	97.49
146	96	0	0.13	0	0	0.11	0.01	0	96.29
147	96	0	0.08	0	0.04	0.06	0.03	0.01	96.5
148	96	0	0.12	0	0.02	0.08	0.04	0.01	96.23
149	97	0	0.09	0	0.04	0.07	0	0.01	96.73
150	96	0	0.14	0	0	0.07	0.01	0.01	96.67

	Fe	Si	Cu	Ni	P	Mn	S	V	Total
151	98	0	0.11	0	0	0.05	0	0.01	97.76
152	97	0	0.08	0	0.03	0.06	0	0	97.41
153	96	0	0.05	0	0.03	0.06	0.1	0.01	95.9
154	97	0	0.11	0	0	0.05	0	0.02	96.73
155	97	0	0.11	0	0	0.05	0.02	0.01	97.55
156	93	0	0.12	0	0.02	0.09	0	0	93.45
157	96	0	0.09	0	0.01	0.07	0	0.03	96.14
158	97	0	0.11	0	0.04	0.05	0.01	0.01	97.23
159	98	0	0.08	0	0.04	0.09	0.03	0.01	98.25
160	97	0	0.07	0	0.01	0.06	0.01	0.03	96.8
161	97	0	0.09	0	0.02	0.06	0.01	0.01	97.48
162	98	0	0.06	0	0	0.08	0	0	97.79
163	95	0	0.15	0	0.01	0.08	0.03	0	95.76
164	97	0	0.14	0	0.03	0.08	0.01	0.02	97.45
165	97	0	0.17	0	0	0.09	0	0.01	97.45
166	93	0	0.07	0	0.02	0.07	0.02	0	93.34
167	97	0	0.14	0	0	0.05	0.1	0.02	96.9
168	96	0	0.09	0	0	0.1	0.2	0.02	96.34
169	95	0	0.13	0	0	0.05	0	0.04	95.46
170	96	0	0.11	0	0.01	0.05	0	0.01	95.72
171	96	0	0.11	0.1	0.05	0.09	0	0.02	96.21
172	96	0	0.11	0	0.02	0.09	0.01	0.01	96.73
173	97	0	0.1	0	0	0.06	0.11	0.01	96.97
174	97	0	0.02	0	0	0.05	0.15	0	97.19
175	96	0	0.12	0.1	0	0.05	0.02	0	95.81
176	97	0	0.1	0	0.03	0.08	0	0.02	96.99
177	98	0	0.13	0	0.03	0	0.01	0.02	98.33
178	98	0	0.08	0	0.05	0.08	0.04	0	98.38
179	98	0	0.12	0	0.02	0.06	0.04	0.01	97.8
180	95	0	0.12	0	0.02	0.08	0.02	0	95.11
181	98	0	0.12	0	0	0.11	0	0.01	98.37
182	97	0	0.06	0.1	0.03	0.01	0.03	0.02	97.56
183	97	0	0.12	0	0.04	0.07	0.02	0.02	97.5
184	97	0	0.03	0	0.03	0.1	0.01	0.01	97.18
185	97	0	0.15	0	0.04	0.02	0.01	0	97.27
186	97	0	0.12	0	0.02	0.07	0	0.01	96.99
187	96	0	0.09	0	0	0.08	0.02	0	96.62
188	98	0	0.12	0	0.05	0.1	0.01	0	97.96
189	97	0	0.09	0	0.05	0.09	0	0	97.24
190	97	0	0.1	0	0	0.08	0.1	0	96.99
191	96	0	0.08	0	0	0.08	0	0.04	96.49
192	96	0	0.03	0	0.04	0.07	0.03	0.01	95.78
193	96	0	0.1	0	0.03	0.06	0	0.04	96.55
194	95	0	0.13	0	0.03	0.07	0	0	95.18
195	95	0	0.06	0	0	0.06	0	0	95.27
196	95	0	0.14	0	0.02	0.09	0.01	0.01	95.69
197	96	0	0.17	0	0.01	0.15	0.03	0.02	96.28
198	96	0	0.09	0	0.01	0.06	0	0.01	95.79
199	97	0	0.1	0	0	0.02	0	0.02	97.44
200	97	0	0.07	0	0.02	0.07	0	0.01	97.35

Appendix G: EPMA of Merv Iron and Steel

	Fe	Si	Cu	Ni	P	Mn	S	V	Total
201	96	0	0.1	0	0	0.08	0	0.01	96.6
202	97	0	0.09	0	0.04	0.06	0	0.01	97
203	96	0	0.1	0	0.03	0.15	0.01	0.01	95.9
204	97	0	0.13	0	0.03	0.04	0	0.01	96.91
205	97	0	0.1	0	0	0.04	0.04	0	97.15
206	97	0	0.09	0	0.02	0.05	0	0.02	97.34
207	98	0	0.09	0	0.01	0.08	0	0.02	97.91
208	97	0	0.08	0	0	0.07	0.02	0	97.24
209	97	0	0.06	0	0.02	0.06	0.02	0	97.58
210	96	0	0.14	0	0.03	0.08	0.02	0.01	96
211	97	0	0.12	0	0.06	0.08	0.01	0	97.09
212	96	0	0.09	0	0.01	0.09	0.05	0.01	95.88
213	96	0	0.15	0	0.03	0.03	0.03	0	96.6
average	**97**	**0**	**0.1**	**0**	**0.02**	**0.07**	**0.02**	**0.01**	**97.04**
stdev	***1.2***	***0***	***0.03***	***0***	***0***	***0***	***0.04***	***0.01***	***1.23***

Appendix H : EPMA of Selected Merv Glass Fragments

small find #	color	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	PbO	BaO	SO_3	Cl	TiO_2	MnO	Fe_2O_3	CoO	CuO	Total
9506	blue	13.5	3.8	3.5	59.6	0.3	3.7	9.1	0.2	0.0	0.4	0.6	0.1	0.2	0.5	0.0	0.2	95.8
		13.9	3.6	3.5	63.5	0.4	4.2	9.4	0.0	0.0	0.4	0.6	0.1	0.1	0.5	0.0	0.1	100.3
		14.6	3.6	3.3	62.3	0.3	4.1	9.4	0.0	0.0	0.4	0.6	0.1	0.1	0.5	0.0	0.0	99.5
average	***9506***	***14.0***	***3.7***	***3.5***	***61.8***	***0.3***	***4.0***	***9.3***	***0.1***	***0.0***	***0.4***	***0.6***	***0.1***	***0.1***	***0.5***	***0.0***	***0.1***	***98.5***
standard deviation		*0.5*	*0.1*	*0.1*	*2.0*	*0.1*	*0.3*	*0.2*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.1*	
		Na_2O	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**PbO**	**BaO**	**SO_3**	**Cl**	**TiO_2**	**MnO**	**Fe_2O_3**	**CoO**	**CuO**	**Total**
8591	light green	11.9	3.2	6.5	58.4	0.0	4.4	8.6	0.0	0.0	0.3	0.8	0.2	0.0	0.9	0.0	0.0	95.2
		15.1	3.1	6.3	58.6	0.0	4.3	8.7	0.0	0.1	0.4	0.8	0.2	0.1	0.9	0.0	0.0	98.7
		15.7	3.3	6.9	59.7	0.0	4.4	8.6	0.0	0.1	0.4	1.0	0.3	0.0	1.0	0.0	0.9	102.5
average	***8591***	***14.2***	***3.2***	***6.6***	***58.9***	***0.0***	***4.4***	***8.6***	***0.0***	***0.1***	***0.4***	***0.8***	***0.2***	***0.0***	***0.9***	***0.0***	***0.3***	***98.7***
standard deviation		*2.0*	*0.1*	*0.3*	*0.7*	*0.0*	*0.1*	*0.1*	*0.0*	*0.0*	*0.1*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.5*	
		Na_2O	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**PbO**	**BaO**	**SO_3**	**Cl**	**TiO_2**	**MnO**	**Fe_2O_3**	**CoO**	**CuO**	**Total**
8579	light green	13.2	3.3	6.5	60.0	0.0	4.7	7.1	0.0	0.1	0.4	0.7	0.3	0.0	0.9	0.0	0.1	97.2
		13.7	3.5	6.8	61.1	0.0	4.7	7.0	0.1	0.1	0.5	0.7	0.3	0.1	1.1	0.0	0.0	99.6
		14.9	3.6	6.7	61.0	0.0	4.5	6.6	0.0	0.1	0.5	0.7	0.2	0.1	1.1	0.0	0.1	100.3
average	***8579***	***13.9***	***3.4***	***6.6***	***60.7***	***0.0***	***4.6***	***6.9***	***0.0***	***0.1***	***0.5***	***0.7***	***0.3***	***0.1***	***1.0***	***0.0***	***0.0***	***99.0***
standard deviation		*0.9*	*0.2*	*0.2*	*0.6*	*0.0*	*0.1*	*0.2*	*0.1*	*0.0*	*0.1*	*0.0*	*0.0*	*0.1*	*0.1*	*0.0*	*0.0*	
		Na_2O	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**PbO**	**BaO**	**SO_3**	**Cl**	**TiO_2**	**MnO**	**Fe_2O_3**	**CoO**	**CuO**	**Total**
9501	clear	13.5	4.1	3.5	65.6	0.0	3.7	8.8	0.0	0.2	0.4	0.5	0.2	1.6	0.5	0.0	0.0	102.7
		12.9	3.9	3.6	63.8	0.0	3.8	9.1	0.0	0.0	0.5	0.6	0.2	1.7	0.5	0.0	0.0	100.5
average	***9501***	***13.2***	***4.0***	***3.6***	***64.7***	***0.0***	***3.7***	***9.0***	***0.0***	***0.1***	***0.5***	***0.5***	***0.2***	***1.7***	***0.5***	***0.0***	***0.0***	***101.6***
standard deviation		*0.3*	*0.1*	*0.1*	*0.9*	*0.0*	*0.1*	*0.2*	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*	
		Na_2O	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**PbO**	**BaO**	**SO_3**	**Cl**	**TiO_2**	**MnO**	**Fe_2O_3**	**CoO**	**CuO**	**Total**
8600	green	13.8	4.9	8.1	57.2	0.0	4.4	8.6	0.0	0.0	0.4	0.7	0.4	0.1	1.3	0.0	0.0	100.1
		13.9	4.9	8.3	57.3	0.0	4.4	8.8	0.0	0.0	0.4	0.7	0.3	0.1	1.3	0.0	0.0	100.4
average	***8600***	***13.9***	***4.9***	***8.2***	***57.3***	***0.0***	***4.4***	***8.7***	***0.0***	***0.0***	***0.4***	***0.7***	***0.3***	***0.1***	***1.3***	***0.0***	***0.0***	***100.1***
standard deviation		*0.0*	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	PbO	BaO	SO_3	Cl	TiO_2	MnO	Fe_2O_3	CoO	CuO	Total
8596 light blue	9.6	3.0	4.6	65.8	0.2	4.0	8.9	0.0	0.0	0.2	0.7	0.1	0.1	0.5	0.0	0.0	97.6
	12.9	2.8	4.2	65.2	0.2	4.0	9.2	0.1	0.0	0.6	0.6	0.1	0.0	0.4	0.0	0.0	100.3
	13.5	3.0	4.1	66.0	0.3	3.8	9.0	0.0	0.1	0.5	0.6	0.1	0.0	0.3	0.0	0.0	101.6
average 8596	***12.0***	***2.9***	***4.3***	***65.7***	***0.2***	***3.9***	***9.0***	***0.0***	***0.0***	***0.4***	***0.6***	***0.1***	***0.0***	***0.4***	***0.0***	***0.0***	***99.8***
standard deviation	*2.1*	*0.1*	*0.2*	*0.4*	*0.0*	*0.1*	*0.1*	*0.0*	*0.0*	*0.2*	*0.0*	*0.0*	*0.0*	*0.1*	*0.0*	*0.0*	

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	PbO	BaO	SO_3	Cl	TiO_2	MnO	Fe_2O_3	CoO	CuO	Total
8580 dark brown	15.3	4.5	8.5	57.3	0.4	5.0	8.4	0.0	0.0	1.0	0.9	0.2	0.0	0.9	0.0	0.0	102.5
	15.4	4.3	7.6	58.1	0.3	4.8	7.9	0.0	0.0	1.0	1.0	0.2	0.0	0.9	0.1	0.0	101.5
	15.7	5.3	8.1	58.9	0.2	4.5	6.8	0.0	0.0	0.9	0.8	0.2	0.0	1.0	0.0	0.0	102.6
	15.9	5.0	7.5	55.2	0.4	4.9	7.4	0.0	0.0	0.8	0.9	0.2	0.1	0.6	0.0	0.0	98.9
average 8580	***15.6***	***4.8***	***7.9***	***57.4***	***0.3***	***4.8***	***7.6***	***0.0***	***0.0***	***0.9***	***0.9***	***0.2***	***0.0***	***0.9***	***0.0***	***0.0***	**101.3**
standard deviation	*0.3*	*0.4*	*0.5*	*1.6*	*0.1*	*0.2*	*0.7*	*0.0*	*0.0*	*0.1*	*0.1*	*0.0*	*0.0*	*0.2*	*0.0*	*0.0*	

Summary of MGK 4 Glass

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	PbO	BaO	SO_3	Cl	TiO_2	MnO	Fe_2O_3	CoO	CuO	Total
9506	14.0	3.7	3.5	61.8	0.3	4.0	9.3	0.1	0.0	0.4	0.6	0.1	0.1	0.5	0.0	0.1	98.5
8591	14.2	3.2	6.6	58.9	0.0	4.4	8.6	0.0	0.1	0.4	0.8	0.2	0.0	0.9	0.0	0.3	98.7
8579	13.9	3.4	6.6	60.7	0.0	4.6	6.9	0.0	0.1	0.5	0.7	0.3	0.1	1.0	0.0	0.0	99.0
9501	13.2	4.0	3.6	64.7	0.0	3.7	9.0	0.0	0.1	0.5	0.5	0.2	1.7	0.5	0.0	0.0	101.6
8600	13.9	4.9	8.2	57.3	0.0	4.4	8.7	0.0	0.0	0.4	0.7	0.3	0.1	1.3	0.0	0.0	100.1
8596	12.0	2.9	4.3	65.7	0.2	3.9	9.0	0.0	0.0	0.4	0.6	0.1	0.0	0.4	0.0	0.0	99.8
8580	15.6	4.8	7.9	57.4	0.3	4.8	7.6	0.0	0.0	0.9	0.9	0.2	0.0	0.9	0.0	0.0	101.3
average of samples	***13.8***	***3.8***	***5.8***	***60.9***	***0.1***	***4.3***	***8.4***	***0.0***	***0.0***	***0.5***	***0.7***	***0.2***	***0.3***	***0.8***	***0.0***	***0.1***	***99.8***
standard deviation	*1.1*	*0.8*	*2.0*	*3.4*	*0.2*	*0.4*	*0.9*	*0.0*	*0.0*	*0.2*	*0.1*	*0.1*	*0.6*	*0.3*	*0.0*	*0.1*	*1.2*

Appendix I: Number of Crucibles in Pit

To assess the weight of crucible material in a typical 15 litres of volume of the pit, two samples were excavated out of the pit, one from the top of the pit and one from the bottom of the pit. It was considered that the remains in the pit were tightly packed whereas the sample in the bucket was more loosely packed. In order to get a more realistic sample, the 15 litre bucket was filled "over the top" so it was more like 18 litres of loosely packed material which when packed down would have been nearer 15 litres of tightly packed material. The crucible fragments were then removed and weighed. To increase the number of samples while keeping to standard British excavating methods, the weight of crucible fragments from several 10 liter flotation samples taken from the pit were also used.

Samples #1	801	grams in 15 litres	=	53.4	g per litre
Samples #2	1060	grams in 15 litres	=	70.6	g per litre
Flot sample #1	1920	grams in 10 litres	=	192.0	g per litre
Flot sample #2	525	grams in 10 litres	=	52.5	g per litre
Flot sample #3	756	grams in 10 litres	=	75.6	g per litre
Flot sample #4	687	grams in 10 litres	=	68.7	g per litre
Flot sample #5	376	grams in 10 litres	=	37.6	g per litre
Flot sample #6	1056	grams in 10 litres	=	105.6	g per litre
		average		82.0	g per litre

Number of crucible in the pit:

12,282 litres total in pit
x 82 grams average of crucible material per litre
1,007,124 average estimated grams of crucible material in pit

Place	Sample Number	object
Kuva	# 1	cast iron object
Akhsiket	# 2	crucible
Kuva	# 3	crucible
Kuva	# 4	crucible
Termez	# 5	bulat
Akhsiket	# 7	agglomerate
Pap	# 9	crucible
Pap	# 10	crucible
Pap	# 11	crucible
Akhsiket	# 12	crucible
Akhsiket	# 13	crucible and slag
Akhsiket	# 15	crucible
Akhsiket	# 16 A	crucible and slag
Akhsiket	# 16 B	crucible and slag
Akhsiket	# 17 A	crucible top
Akhsiket	# 17 b	crucible bottom
Akhsiket	# 18	green slag
Akhsiket	# 19 A	crucible top
Akhsiket	# 19 B	crucible bottom
Akhsiket	# 20 A	crucible and slag
Akhsiket	# 20 B	crucible and slag
Akhsiket	# 23	crucible and slag

Appendix K: EPMA of Uzbekistan Crucibles

10 um area	sample #	**BaO**	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Akhsiket	2 wall	0.0	0.3	3.3	1.7	0.2	58.7	5.1	0.0	23.9	0.5	0.8	0.2	0.0	0.0	0.1	0.1	95.0
Akhsiket	2 wall	0.0	0.3	0.2	2.0	0.3	56.4	9.5	0.0	27.1	0.6	0.4	0.2	0.0	0.0	0.0	0.1	97.2
Akhsiket	2 wall	0.1	0.2	0.1	1.7	0.3	52.7	7.8	0.0	29.6	0.6	1.1	0.3	0.0	0.0	0.0	0.1	94.5
average	**2 wall**	**0.0**	**0.3**	**1.2**	**1.8**	**0.3**	**55.9**	**7.5**	**0.0**	**26.9**	**0.6**	**0.8**	**0.2**	**0.0**	**0.0**	**0.0**	**0.1**	**95.5**
standard deviation		*0.0*	*0.1*	*1.8*	*0.2*	*0.1*	*3.0*	*2.2*	*0.0*	*2.9*	*0.1*	*0.3*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	
Akhsiket	12 wall	0.0	0.3	0.4	7.8	0.5	69.0	1.5	0.0	18.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	98.1
Akhsiket	12 wall	0.0	0.2	0.5	5.0	0.1	71.4	2.1	0.0	19.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	98.7
Akhsiket	12 wall	0.0	0.2	0.5	5.1	0.3	69.6	2.3	0.0	21.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0	99.6
average	**12 wall**	**0.0**	**0.2**	**0.5**	**6.0**	**0.3**	**70.0**	**1.9**	**0.0**	**19.6**	**0.2**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**98.8**
standard deviation		*0.0*	*0.1*	*0.0*	*1.6*	*0.2*	*1.2*	*0.4*	*0.0*	*1.6*	*0.1*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	
Akhsiket	15 wall	0.0	0.1	0.1	1.7	0.1	63.1	1.2	0.0	31.0	0.3	0.4	0.1	0.0	0.0	0.0	0.0	98.1
Akhsiket	15 wall	0.0	0.2	0.1	1.5	0.0	60.6	2.0	0.0	31.9	0.3	0.7	0.2	0.0	0.0	0.0	0.0	97.5
Akhsiket	15 wall	0.0	0.1	0.1	2.5	0.2	64.4	1.4	0.0	27.0	0.3	0.5	0.2	0.0	0.0	0.0	0.0	96.6
average	**15 wall**	**0.0**	**0.1**	**0.1**	**1.9**	**0.1**	**62.7**	**1.5**	**0.0**	**30.0**	**0.3**	**0.5**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**97.4**
standard deviation		*0.0*	*0.1*	*0.0*	*0.5*	*0.1*	*1.9*	*0.4*	*0.0*	*2.6*	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	
Akhsiket	15 inclusion	0.0	0.0	0.2	0.1	0.0	72.4	2.9	0.0	23.2	0.7	0.4	0.1	0.0	0.0	0.0	0.0	100.1
Akhsiket	16 wall	0.0	0.0	0.2	2.8	0.2	75.9	1.5	0.0	15.6	1.4	1.0	0.2	0.0	0.0	0.0	0.0	98.7
Akhsiket	16 wall	0.0	0.0	0.1	2.0	0.2	67.5	1.0	0.0	27.8	0.9	0.7	0.2	0.0	0.0	0.0	0.0	100.5
Akhsiket	16 wall	0.1	0.0	0.7	2.9	0.2	73.3	1.3	1.0	16.1	1.1	0.8	0.2	0.0	0.0	0.0	0.0	97.8
average	**16 wall**	**0.1**	**0.0**	**0.3**	**2.6**	**0.2**	**72.2**	**1.2**	**0.3**	**19.8**	**1.1**	**0.9**	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**99.0**
standard deviation		*0.0*	*0.0*	*0.3*	*0.5*	*0.0*	*4.3*	*0.2*	*0.6*	*6.9*	*0.2*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	

		BaO	P_2O_5	CaO	K_2O	Na_2O	SiO_2	FeO	MnO	Al_2O_3	MgO	TiO2	V_2O_5	SO_3	NiO	CuO	Cl	Total
Akhsiket	17 wall	0.0	0.1	0.2	0.2	0.1	55.3	2.0	0.0	37.3	0.3	0.3	0.1	0.0	0.0	0.0	0.0	96.1
Akhsiket	17 wall	0.0	0.1	0.1	0.3	0.2	57.3	2.2	0.0	36.3	0.5	0.3	0.1	0.0	0.0	0.0	0.0	97.4
Akhsiket	17 wall	0.0	0.2	0.2	1.0	0.3	53.6	2.4	0.0	35.8	0.6	0.2	0.1	0.0	0.0	0.0	0.0	94.4
average	**17 wall**	**0.0**	**0.1**	**0.2**	**0.5**	**0.2**	**55.4**	**2.2**	**0.0**	**36.5**	**0.5**	**0.3**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**96.0**
standard deviation		*0.0*	*0.1*	*0.0*	*0.5*	*0.1*	*1.9*	*0.2*	*0.0*	*0.8*	*0.1*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	
Akhsiket	19 wall	0.0	0.0	0.2	1.3	0.4	63.0	1.6	0.0	37.3	0.5	0.6	0.1	0.0	0.0	0.0	0.0	105.1
Akhsiket	19 wall	0.0	0.9	1.1	0.8	0.5	53.5	2.2	0.0	35.9	0.4	0.7	0.2	0.0	0.0	0.0	0.0	96.1
Akhsiket	19 wall	0.0	0.1	0.2	1.2	0.5	58.7	2.6	0.0	35.3	0.4	0.6	0.1	0.0	0.0	0.0	0.0	99.6
Akhsiket	19 wall	0.1	0.0	0.2	1.1	0.4	53.8	2.7	0.0	37.2	0.5	1.7	0.4	0.0	0.0	0.0	0.0	98.0
average	**19 wall**	**0.0**	**0.3**	**0.5**	**1.0**	**0.4**	**55.3**	**2.5**	**0.0**	**36.1**	**0.4**	**1.0**	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**97.9**
standard deviation		*0.0*	*0.4*	*0.5*	*0.2*	*0.0*	*4.6*	*0.5*	*0.0*	*1.0*	*0.1*	*0.5*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	
Akhsiket	23 wall	0.0	0.0	0.1	1.6	0.2	63.7	0.2	0.0	33.0	0.4	0.6	0.1	0.0	0.0	0.0	0.0	100.0
Akhsiket	23 wall	0.0	0.1	0.1	3.2	0.3	66.8	0.5	0.0	29.1	0.7	0.5	0.1	0.0	0.0	0.0	0.0	101.5
Akhsiket	23 wall	0.0	0.1	0.1	3.1	0.3	58.1	0.4	0.0	26.7	0.8	0.8	0.2	0.0	0.0	0.0	0.0	90.8
Akhsiket	23 wall	0.0	0.0	0.1	1.4	0.1	57.1	0.4	0.0	34.9	0.5	1.1	0.2	0.0	0.0	0.0	0.0	95.9
Akhsiket	23 wall	0.1	0.1	0.2	2.7	0.5	59.7	0.7	0.0	28.7	1.7	0.9	0.3	0.0	0.0	0.0	0.0	95.6
average	**23 wall**	**0.0**	**0.1**	**0.1**	**2.4**	**0.3**	**58.3**	**0.5**	**0.0**	**30.1**	**1.0**	**0.9**	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**94.1**
standard deviation		*0.0*	*0.0*	*0.0*	*0.8*	*0.1*	*4.1*	*0.2*	*0.0*	*3.4*	*0.6*	*0.2*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	

Summary		BaO	P_2O_5	CaO	K_2O	Na_2O	SiO_2	FeO	MnO	Al_2O_3	MgO	TiO2	V_2O_5	SO_3	NiO	CuO	Cl	Total
Akhsiket	2	0.0	0.3	1.2	1.8	0.3	55.9	7.5	0.0	26.9	0.6	0.8	0.2	0.0	0.0	0.0	0.1	95.5
Akhsiket	12	0.0	0.2	0.5	6.0	0.3	70.0	1.9	0.0	19.6	0.2	0.1	0.0	0.0	0.0	0.0	0.0	98.8
Akhsiket	15	0.0	0.1	0.1	1.9	0.1	62.7	1.5	0.0	30.0	0.3	0.5	0.1	0.0	0.0	0.0	0.0	97.4
Akhsiket	16	0.1	0.0	0.3	2.6	0.2	72.2	1.2	0.3	19.8	1.1	0.9	0.2	0.0	0.0	0.0	0.0	99.0
Akhsiket	17	0.0	0.1	0.2	0.5	0.2	55.4	2.2	0.0	36.5	0.5	0.3	0.1	0.0	0.0	0.0	0.0	96.0
Akhsiket	19	0.0	0.3	0.5	1.0	0.4	55.3	2.5	0.0	36.1	0.4	1.0	0.2	0.0	0.0	0.0	0.0	97.9
Akhsiket	23	0.0	0.1	0.1	2.4	0.3	58.3	0.5	0.0	30.1	1.0	0.9	0.2	0.0	0.0	0.0	0.0	94.1
Average	**Akshiket**	**0.0**	**0.2**	**0.4**	**2.3**	**0.3**	**61.4**	**2.5**	**0.1**	**28.4**	**0.6**	**0.6**	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**97.0**
standard deviation		*0.0*	*0.1*	*0.4*	*1.8*	*0.1*	*7.1*	*2.3*	*0.1*	*6.9*	*0.4*	*0.4*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	

	sample #	BaO	P_2O_5	CaO	K_2O	Na_2O	SiO_2	FeO	MnO	Al_2O_3	MgO	TiO2	V_2O_5	SO_3	NiO	CuO	Cl	Total
Pap	9 wall	0.1	0.2	0.1	1.6	0.1	62.7	1.5	0.0	27.1	0.6	2.0	0.4	0.0	0.0	0.0	0.0	96.5
Pap	9 wall	0.1	0.2	0.1	1.8	0.1	61.1	1.1	0.0	29.2	0.4	1.2	0.3	0.0	0.0	0.0	0.0	95.5
Pap	9 wall	0.0	0.1	0.2	2.6	0.2	69.8	0.9	0.0	20.6	0.3	0.4	0.1	0.0	0.0	0.0	0.0	95.4
average	**9 wall**	**0.1**	**0.2**	**0.2**	**2.0**	**0.1**	**64.5**	**1.2**	**0.0**	**25.6**	**0.4**	**1.2**	**0.3**	**0.0**	**0.0**	**0.0**	**0.0**	**95.8**
standard deviation		*0.0*	*0.1*	*0.1*	*0.5*	*0.0*	*4.6*	*0.3*	*0.0*	*4.5*	*0.1*	*0.8*	*0.2*	*0.0*	*0.0*	*0.0*	*0.0*	
Pap	10 wall	0.0	0.1	0.1	0.1	0.0	57.3	0.3	0.0	32.4	0.6	0.9	0.1	0.0	0.0	0.0	0.0	92.1
Pap	10 wall	0.1	0.0	0.2	1.7	0.3	55.3	0.4	0.0	36.4	0.6	2.3	0.4	0.0	0.0	0.0	0.0	97.7
Pap	10 wall	0.0	0.0	0.1	0.1	0.0	85.5	0.1	0.0	16.6	0.1	0.1	0.0	0.0	0.0	0.0	0.0	102.6
Pap	10 wall	0.1	0.1	0.2	1.6	0.2	53.4	0.4	0.0	30.5	0.5	2.4	0.5	0.0	0.0	0.0	0.0	89.9
Pap	10 wall	0.0	0.0	0.9	1.1	0.2	55.5	0.5	0.0	35.7	0.9	0.7	0.2	0.0	0.0	0.0	0.0	95.8
average	**10 wall**	**0.0**	**0.0**	**0.3**	**0.9**	**0.1**	**61.4**	**0.3**	**0.0**	**30.3**	**0.5**	**1.3**	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**95.6**
standard deviation		*0.0*	*0.0*	*0.3*	*0.8*	*0.1*	*13.5*	*0.2*	*0.0*	*8.1*	*0.3*	*1.0*	*0.2*	*0.0*	*0.0*	*0.0*	*0.0*	
Pap	11 wall	0.0	0.2	1.6	0.6	0.2	57.7	1.2	0.1	34.1	0.6	0.8	0.2	0.0	0.0	0.0	0.0	97.2
Pap	11 wall	0.1	0.1	0.3	0.7	0.2	57.2	1.3	0.7	34.5	0.7	0.3	0.1	0.0	0.0	0.0	0.0	96.2
Pap	11 wall	0.1	0.1	0.3	1.2	0.2	55.4	1.6	0.4	34.1	0.7	3.1	0.8	0.0	0.0	0.0	0.0	97.8
average	**11 wall**	**0.1**	**0.1**	**0.3**	**1.0**	**0.2**	**56.3**	**1.4**	**0.5**	**34.3**	**0.7**	**1.7**	**0.4**	**0.0**	**0.0**	**0.0**	**0.0**	**97.0**
standard deviation		*0.1*	*0.1*	*0.7*	*0.3*	*0.0*	*1.2*	*0.2*	*0.3*	*0.3*	*0.0*	*1.5*	*0.4*	*0.0*	*0.0*	*0.0*	*0.0*	

Summary		BaO	P_2O_5	CaO	K_2O	Na_2O	SiO_2	FeO	MnO	Al_2O_3	MgO	TiO2	V_2O_5	SO_3	NiO	CuO	Cl	Total
Pap	9	0.1	0.2	0.2	2.0	0.1	64.5	1.2	0.0	25.6	0.4	1.2	0.3	0.0	0.0	0.0	0.0	95.8
Pap	10	0.0	0.0	0.3	0.9	0.1	61.4	0.3	0.0	30.3	0.5	1.3	0.2	0.0	0.0	0.0	0.0	95.6
Pap	11	0.1	0.1	0.3	1.0	0.2	56.3	1.4	0.5	34.3	0.7	1.7	0.4	0.0	0.0	0.0	0.0	97.0
Average	**Pap**	**0.1**	**0.1**	**0.3**	**1.3**	**0.2**	**60.7**	**1.0**	**0.2**	**30.1**	**0.5**	**1.4**	**0.3**	**0.0**	**0.0**	**0.0**	**0.0**	**96.1**
standard deviation		*0.0*	*0.1*	*0.1*	*0.6*	*0.0*	*4.2*	*0.6*	*0.3*	*4.3*	*0.1*	*0.3*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	

Summary			**BaO**	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Average	Akshiket		0.0	0.2	0.4	2.3	0.3	61.4	2.5	0.1	28.4	0.6	0.6	0.2	0.0	0.0	0.0	0.0	97.0
Average	Pap		0.1	0.1	0.3	1.3	0.2	60.7	1.0	0.2	30.1	0.5	1.4	0.3	0.0	0.0	0.0	0.0	96.1
Average	**Uzbekistan**		**0.1**	**0.1**	**0.3**	**1.8**	**0.2**	**61.1**	**1.7**	**0.1**	**29.3**	**0.6**	**1.0**	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**96.5**
standard deviation			0.0	0.0	0.1	0.7	0.1	0.5	1.1	0.1	1.2	0.0	0.5	0.1	0.0	0.0	0.0	0.0	

Black glaze			**BaO**	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Akhsiket		2 glaze	0.1	0.6	13.4	2.6	2.8	51.2	2.5	0.1	13.0	1.4	0.3	0.1	0.1	0.0	0.2	0.6	88.8
Akhsiket		15 glaze	0.0	0.3	6.1	2.6	0.2	64.9	2.4	0.0	19.0	0.5	0.4	0.1	0.0	0.0	0.0	0.0	96.8
Akhsiket		17 glaze	0.1	0.2	4.5	1.4	0.5	55.7	4.9	0.0	28.4	0.6	0.5	0.1	0.1	0.0	0.0	0.0	96.8
Akhsiket		23 glaze	0.4	0.5	8.3	2.1	0.5	57.9	1.8	3.5	17.9	0.9	0.6	0.1	0.1	0.0	0.0	0.0	94.5
Pap		9 glaze	0.6	0.0	1.0	2.1	0.2	65.8	1.4	6.3	15.9	0.4	0.9	0.2	0.0	0.0	0.0	0.0	95.0
Pap		10 glaze	0.9	0.0	1.2	0.9	0.2	63.4	0.7	7.8	16.4	0.3	0.5	0.1	0.1	0.0	0.0	0.0	92.6

Copper-processing Crucibles			**BaO**	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Kuva		3 wall	0.0	0.0	0.1	2.3	0.2	54.2	0.7	0.0	40.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	98.7
Kuva		3 wall	0.1	0.1	4.4	2.8	0.3	64.2	4.2	0.1	17.7	1.4	0.5	0.1	0.0	0.0	0.1	0.0	96.0
Kuva		3 wall	0.0	0.1	0.6	2.6	0.3	57.8	1.7	0.0	33.0	0.7	0.5	0.1	0.0	0.0	0.1	0.0	97.5
average		**3 wall**	**0.1**	**0.1**	**1.7**	**2.6**	**0.2**	**58.7**	**2.2**	**0.0**	**30.5**	**0.8**	**0.3**	**0.1**	**0.0**	**0.0**	**0.1**	**0.0**	**97.4**
standard deviation			*0.0*	*0.1*	*2.4*	*0.3*	*0.0*	*5.1*	*1.8*	*0.0*	*11.8*	*0.6*	*0.3*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	
Kuva		4 wall	0.0	0.0	0.2	2.6	0.1	58.6	1.7	0.0	30.5	0.5	0.6	0.2	0.0	0.0	0.1	0.0	95.0
Kuva		4 wall	0.1	0.1	0.7	2.9	0.2	63.3	2.4	0.0	25.4	0.6	0.6	0.2	0.0	0.0	0.1	0.0	96.6
Kuva		4 wall	0.1	0.4	0.3	2.7	0.3	61.2	6.7	0.0	23.1	0.9	0.7	0.2	0.0	0.0	0.2	0.0	96.6
average		**4 wall**	**0.1**	**0.2**	**0.4**	**2.7**	**0.2**	**61.0**	**3.6**	**0.0**	**26.3**	**0.7**	**0.6**	**0.2**	**0.0**	**0.0**	**0.2**	**0.0**	**96.1**
standard deviation			*0.0*	*0.2*	*0.3*	*0.1*	*0.1*	*2.4*	*2.7*	*0.0*	*3.8*	*0.2*	*0.1*	*0.0*	*0.0*	*0.0*	*0.1*	*0.0*	
Kuva	Kuva 3	wall	0.1	0.1	1.7	2.6	0.2	58.7	2.2	0.0	30.5	0.8	0.3	0.1	0.0	0.0	0.1	0.0	97.4
Kuva	Kuva 4	wall	0.1	0.2	0.4	2.7	0.2	61.0	3.6	0.0	26.3	0.7	0.6	0.2	0.0	0.0	0.2	0.0	96.1

sample #		***beam size 10 um***																
		BaO	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Akshi 2	slag	0.1	0.7	14.9	3.6	0.1	50.8	6.1	0.1	13.7	0.9	0.3	0.1	0.0	0.0	0.0	0.0	91.5
Akshi 2	slag	0.0	0.2	17.2	0.7	0.7	46.0	1.4	0.0	27.9	0.2	0.1	0.0	0.0	0.0	0.0	0.0	94.5
Akshi 2	slag	0.0	0.6	9.6	2.8	0.8	56.8	7.0	0.0	16.6	0.7	0.4	0.1	0.0	0.0	0.0	0.0	95.5
Akshi 2	***slag***	***0.0***	***0.5***	***13.9***	***2.4***	***0.5***	***51.2***	***4.9***	***0.0***	***19.4***	***0.6***	***0.3***	***0.1***	***0.0***	***0.0***	***0.0***	***0.0***	*93.8*
		BaO	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Akshi 12	slag	0.0	0.3	18.6	2.8	0.3	52.4	1.1	0.1	19.7	1.3	0.2	0.1	0.0	0.0	0.0	0.0	96.9
Akshi 12	slag	0.1	0.5	20.9	2.9	0.2	49.9	0.9	0.1	18.7	1.3	0.2	0.1	0.0	0.0	0.0	0.0	95.8
Akshi 12	slag	0.0	0.5	34.5	2.0	0.1	40.1	1.2	0.1	14.2	1.4	0.2	0.1	0.0	0.0	0.0	0.0	94.5
Akshi 12	***slag***	***0.0***	***0.4***	***24.7***	***2.5***	***0.2***	***47.5***	***1.1***	***0.1***	***17.6***	***1.3***	***0.2***	***0.1***	***0.0***	***0.0***	***0.0***	***0.0***	*95.7*
		BaO	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Akshi 16?	intereior slag	0.2	0.0	6.8	1.0	0.1	61.2	2.2	15.7	11.3	0.6	0.3	0.1	0.0	0.0	0.0	0.0	99.6
Akshi 16?	intereior slag	0.2	0.0	6.7	1.0	0.1	60.5	2.5	16.1	10.8	0.6	0.3	0.1	0.1	0.0	0.0	0.0	99.0
Akshi 16?	slag	0.2	0.0	6.6	1.0	0.5	60.7	2.4	15.9	11.0	0.6	0.3	0.1	0.0	0.0	0.0	0.0	99.4
Akshi 16	***slag***	***0.2***	***0.0***	***6.7***	***1.0***	***0.3***	***60.8***	***2.4***	***15.9***	***11.0***	***0.6***	***0.3***	***0.1***	***0.0***	***0.0***	***0.0***	***0.0***	*99.3*
Akshi 16?	slag inclusion	0	0.003	0.01	0.02	0.02	107	0	0.02	0	0	0	0.011	0	0	0	0	106.6
		BaO	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Akshi 17	slag	1.3	0.0	1.8	0.5	0.0	56.2	1.4	20.7	8.4	0.4	0.2	0.1	0.3	0.0	0.0	0.1	91.4
Akshi 17	slag	1.3	0.1	2.0	0.7	0.3	55.3	1.3	18.0	11.6	0.3	0.3	0.1	0.2	0.0	0.0	0.0	91.4
Akshi 17	slag	1.5	0.0	1.8	0.7	0.2	55.6	1.2	20.0	9.8	0.3	0.2	0.1	0.2	0.0	0.0	0.0	91.8
Akshi 17	***slag***	***1.4***	***0.0***	***1.9***	***0.7***	***0.2***	***55.7***	***1.3***	***19.6***	***9.9***	***0.3***	***0.2***	***0.1***	***0.2***	***0.0***	***0.0***	***0.0***	*91.5*
		BaO	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Akshi 18	slag	0.1	0.0	4.4	0.9	0.3	60.3	3.8	16.8	9.3	0.7	0.3	0.0	0.0	0.0	0.0	0.0	96.7
Akshi 18	slag	0.1	0.0	4.3	0.8	0.3	60.4	3.8	16.9	9.1	0.7	0.3	0.0	0.0	0.0	0.0	0.0	96.6
Akshi 18	slag	0.1	0.0	4.2	0.9	0.1	61.2	3.9	16.9	9.3	0.7	0.3	0.1	0.0	0.0	0.0	0.0	97.6
Akshi 18	***slag***	***0.1***	***0.0***	***4.3***	***0.9***	***0.2***	***60.6***	***3.8***	***16.8***	***9.2***	***0.7***	***0.3***	***0.1***	***0.0***	***0.0***	***0.0***	***0.0***	*97.0*

		BaO	P_2O_5	CaO	K_2O	Na_2O	SiO_2	FeO	MnO	Al_2O_3	MgO	TiO_2	V_2O_5	SO_3	NiO	CuO	Cl	Total
Akshi 19	slag	1.0	0.1	7.0	1.1	0.2	61.3	2.6	15.2	10.0	0.9	0.3	0.1	0.0	0.0	0.0	0.0	99.7
Akshi 19	slag	0.9	0.0	6.8	1.1	0.1	61.9	2.7	15.3	9.6	0.9	0.2	0.1	0.0	0.0	0.0	0.0	99.7
Akshi 19	slag	1.0	0.0	7.0	1.1	0.4	61.6	2.7	15.6	9.3	0.9	0.2	0.1	0.1	0.0	0.0	0.0	100.0
Akshi 19	***slag***	***1.0***	***0.0***	***6.9***	***1.1***	***0.2***	***61.6***	***2.7***	***15.4***	***9.6***	***0.9***	***0.3***	***0.1***	***0.0***	***0.0***	***0.0***	***0.0***	*99.8*
		BaO	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Akshi no#	slag	1.6	0.0	2.7	0.3	0.1	50.7	3.5	31.3	6.4	0.7	0.2	0.1	0.2	0.0	0.0	0.0	97.8
Akshi	slag	1.6	0.0	2.3	0.7	0.2	56.6	3.0	26.5	6.2	0.6	0.2	0.1	0.2	0.0	0.0	0.0	98.0
Akshi	slag	0.0	0.1	0.2	0.0	0.0	0.0	70.4	0.1	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.2	71.1
Akshi	slag	0.0	0.1	1.1	0.0	0.0	1.7	71.6	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	75.0
Akshi	***slag***	***0.8***	***0.0***	***1.6***	***0.2***	***0.1***	***27.2***	***37.1***	***14.5***	***3.1***	***0.3***	***0.1***	***0.1***	***0.2***	***0.0***	***0.0***	***0.1***	
		BaO	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Pap 9	slag	0.1	0.1	8.6	2.0	0.3	65.8	3.4	0.1	15.3	1.1	0.4	0.1	0.0	0.0	0.0	0.0	97.3
Pap 9	slag	0.1	0.1	7.7	2.2	0.4	65.4	3.9	0.1	16.3	1.0	0.4	0.1	0.0	0.0	0.0	0.0	97.6
Pap 9	slag	0.1	0.1	8.6	2.0	0.5	66.3	3.5	0.1	14.5	1.2	0.4	0.1	0.1	0.0	0.0	0.0	97.5
Pap 9	***slag***	***0.1***	***0.1***	***8.3***	***2.1***	***0.4***	***65.8***	***3.6***	***0.1***	***15.4***	***1.1***	***0.4***	***0.1***	***0.0***	***0.0***	***0.0***	***0.0***	*97.5*
		BaO	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Pap 10	slag	0.1	0.2	7.8	1.8	0.7	56.4	3.4	0.1	17.8	1.3	0.8	0.2	0.1	0.0	0.0	0.0	90.8
Pap 10	slag	0.1	0.4	7.8	2.2	0.8	61.1	2.1	0.1	16.8	1.2	0.7	0.1	0.0	0.0	0.0	0.0	93.4
Pap 10	slag	0.1	0.2	7.2	2.2	0.7	59.6	2.9	0.1	17.2	1.2	0.7	0.2	0.0	0.0	0.0	0.0	92.2
Pap 10	***slag***	***0.1***	***0.3***	***7.6***	***2.1***	***0.7***	***59.1***	***2.8***	***0.1***	***17.3***	***1.2***	***0.7***	***0.2***	***0.0***	***0.0***	***0.0***	***0.0***	*92.1*
		BaO	**P_2O_5**	**CaO**	**K_2O**	**Na_2O**	**SiO_2**	**FeO**	**MnO**	**Al_2O_3**	**MgO**	**TiO_2**	**V_2O_5**	**SO_3**	**NiO**	**CuO**	**Cl**	**Total**
Pap 11	slag	0.2	0.6	7.6	2.6	0.6	57.1	1.9	3.1	21.5	0.9	0.5	0.1	0.1	0.0	0.0	0.0	97.0
Pap 11	slag	0.2	0.7	7.4	2.6	0.5	57.6	2.0	3.1	21.7	0.9	0.5	0.1	0.1	0.0	0.0	0.0	97.2
Pap 11	slag	0.3	0.1	5.0	4.1	0.8	63.2	1.3	3.2	18.6	0.5	0.5	0.1	0.0	0.0	0.0	0.0	97.7
Pap 11	***slag***	***0.2***	***0.4***	***6.7***	***3.1***	***0.6***	***59.3***	***1.8***	***3.1***	***20.6***	***0.7***	***0.5***	***0.1***	***0.1***	***0.0***	***0.0***	***0.0***	*97.3*

Copper slag

		BaO	P_2O_5	CaO	K_2O	Na_2O	SiO_2	FeO	MnO	Al_2O_3	MgO	TiO_2	V_2O_5	SO_3	NiO	CuO	Cl	Total
kuva 3	slag	0.1	0.9	10.5	5.7	1.4	56.3	1.8	0.1	13.4	1.0	0.9	0.2	0.0	0.0	**3.3**	0.0	95.5
Kuva 3	slag	0.1	0.1	9.7	4.0	1.7	53.3	0.7	0.0	26.5	0.4	0.5	0.1	0.0	0.0	0.2	0.0	97.4
Kuva 3	slag	0.1	1.4	15.9	3.8	1.4	50.6	1.9	0.1	11.6	1.2	0.3	0.1	0.0	0.0	**6.2**	0.0	94.6
kuva 3	***slag***	***0.1***	***0.8***	***12.0***	***4.5***	***1.5***	***53.4***	***1.5***	***0.1***	***17.2***	***0.9***	***0.6***	***0.1***	***0.0***	***0.0***	***3.2***	***0.0***	*95.9*
Kuva 3	inclusion	0.0	0.1	0.1	2.4	0.2	56.0	0.9	0.0	38.6	0.4	0.1	0.0	0.0	0.0	0.1	0.0	98.8
Kuva 4	slag	0.2	0.5	5.2	2.2	0.6	39.9	2.0	0.0	7.6	0.4	0.2	0.1	0.0	0.1	19.0	0.0	78.0
Kuva 4	slag	0.1	0.4	4.3	3.2	0.9	45.7	1.5	0.0	10.0	0.3	0.2	0.1	0.0	0.1	14.5	0.0	81.4
kuva 4	***slag***	***0.2***	***0.5***	***4.7***	***2.7***	***0.7***	***42.8***	***1.8***	***0.0***	***8.8***	***0.3***	***0.2***	***0.1***	***0.0***	***0.1***	***16.8***	***0.0***	*79.7*

Summary

		BaO	P_2O_5	CaO	K_2O	Na_2O	SiO_2	FeO	MnO	Al_2O_3	MgO	TiO_2	V_2O_5	SO_3	NiO	CuO	Cl	Total
Akshi 2	*slag*	*0.0*	*0.5*	*13.9*	*2.4*	*0.5*	*51.2*	*4.9*	*0.0*	*19.4*	*0.6*	*0.3*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*93.8*
akshi 12	*slag*	*0.0*	*0.4*	*24.7*	*2.5*	*0.2*	*47.5*	*1.1*	*0.1*	*17.6*	*1.3*	*0.2*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*95.7*
Akshi 16	*slag*	*0.2*	*0.0*	*6.7*	*1.0*	*0.3*	*60.8*	*2.4*	*15.9*	*11.0*	*0.6*	*0.3*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*99.3*
akshi 17	*slag*	*1.4*	*0.0*	*1.9*	*0.7*	*0.2*	*55.7*	*1.3*	*19.6*	*9.9*	*0.3*	*0.2*	*0.1*	*0.2*	*0.0*	*0.0*	*0.0*	*91.5*
Akshi 18	*slag*	*0.1*	*0.0*	*4.3*	*0.9*	*0.2*	*60.6*	*3.8*	*16.8*	*9.2*	*0.7*	*0.3*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*97.0*
akshi 19	*slag*	*1.0*	*0.0*	*6.9*	*1.1*	*0.2*	*61.6*	*2.7*	*15.4*	*9.6*	*0.9*	*0.3*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*99.8*
Pap 9	*slag*	*0.1*	*0.1*	*8.3*	*2.1*	*0.4*	*65.8*	*3.6*	*0.1*	*15.4*	*1.1*	*0.4*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*97.5*
Pap 10	*slag*	*0.1*	*0.3*	*7.6*	*2.1*	*0.7*	*59.1*	*2.8*	*0.1*	*17.3*	*1.2*	*0.7*	*0.2*	*0.0*	*0.0*	*0.0*	*0.0*	*92.1*
Pap 11	*slag*	*0.2*	*0.4*	*6.7*	*3.1*	*0.6*	*59.3*	*1.8*	*3.1*	*20.6*	*0.7*	*0.5*	*0.1*	*0.1*	*0.0*	*0.0*	*0.0*	*97.3*
Cu slag																		
kuva 3	*slag*	*0.1*	*0.8*	*12.0*	*4.5*	*1.5*	*53.4*	*1.5*	*0.1*	*17.2*	*0.9*	*0.6*	*0.1*	*0.0*	*0.0*	*3.2*	*0.0*	*95.9*
kuva 4	*slag*	*0.2*	*0.5*	*4.7*	*2.7*	*0.7*	*42.8*	*1.8*	*0.0*	*8.8*	*0.3*	*0.2*	*0.1*	*0.0*	*0.1*	*16.8*	*0.0*	*79.7*

Appendix M: EPMA of Akhsiket Prills and Termez Ingot

Akhsiket ID	**Fe**	**P**	**Cu**	**Mn**	**S**	**Total**
A 16	97.7	0	0.08	0.14	0	98
A 16	97.5	0	0.11	0.1	0	98
A 16	97.4	0.1	0.11	0.2	0	98
average	**97.5**	**0**	**0.1**	**0.15**	**0**	**98**
A 19	97	0.1	0	0.1	0	97
A 19	96	0.1	0	0.1	0	96
A 19	97	0	0	0.2	0	97
average	**96.7**	**0.1**	**0**	**0.13**	**0**	**97**
A 19 prill 2	95	0.1	0	0.2	0	95

Termez Ingot	**Fe**	**P**	**Cu**	**Mn**	**S**	**Al**	**Ni**	**Si**	**Ti**	**Cr**	**Mg**	**As**	**Ca**	**Ba**	**V**	**Au**	**Ag**	**Total**
1	87.9	0	0	0.03	0	0	0	0	0	0	0	0.03	0.03	0.02	0	0	0	88
2	90.5	0	0.02	0.03	0	0	0	0	0	0	0	0.01	0	0.01	0	0	0.02	91
3	87.5	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	88
4	91.4	0	0.01	0.03	0	0	0	0	0	0	0	0	0	0.01	0	0	0	91
average	**89.3**	**0**	**0.01**	**0.02**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.01**	**0.01**	**0.01**	**0**	**0**	**0.01**	**89**

In the following illustrations in Appendix N, O, and P, the unlabelled arrow points to the sampling location. The photomicrographs were taken using reflected light microscopy, after standard methods of polishing and etching in nital.

KIS # 4

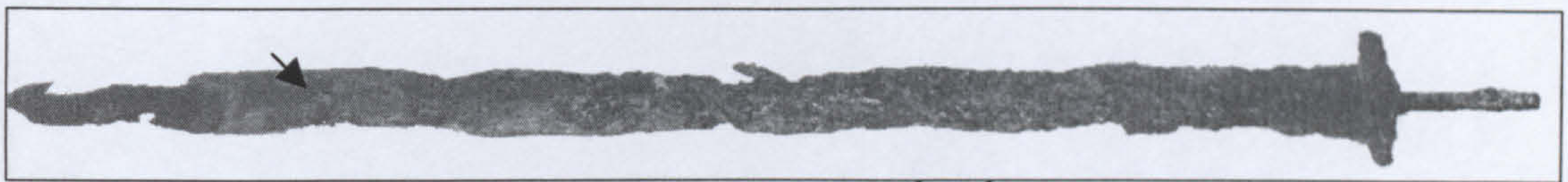


Figure 116a: Double edged sword attributed to 5th–6th century AD.

Kis #	Location	Length	Width	Microstructure
4	Kislovodsk	88 cm	4 cm	Ferrite

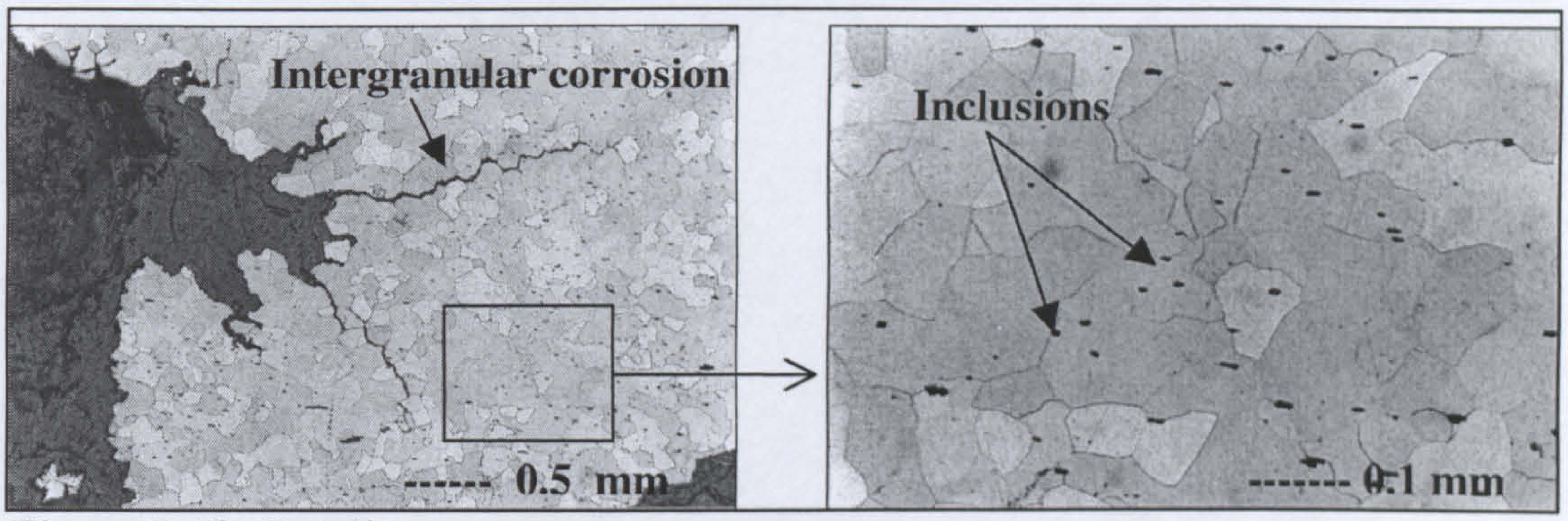


Figure 116b: Detail.

The shape of the sword with the prominent straight guard is reminiscent of European swords. The metallographic sample is composed of corrosion and ferrite. The microstructure also shows a relatively even distribution of non-metallic inclusions appearing as black oval shaped dots. These are believed to be slag. Intergranular corrosion can be clearly observed where the corrosion meets the preserved metal.

KIS # 5:

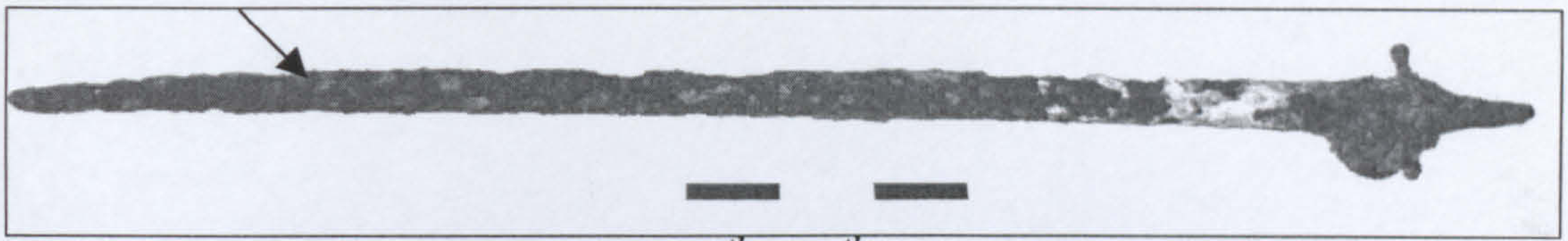


Figure 117a: Sabre attributed to the 10^{th} – 12^{th} century AD.

Kis #	Location	Length	Width	Thickness	Microstructure
5	Ooloo Dorbumly	84 cm	3 cm	0.5 cm	Ferrite

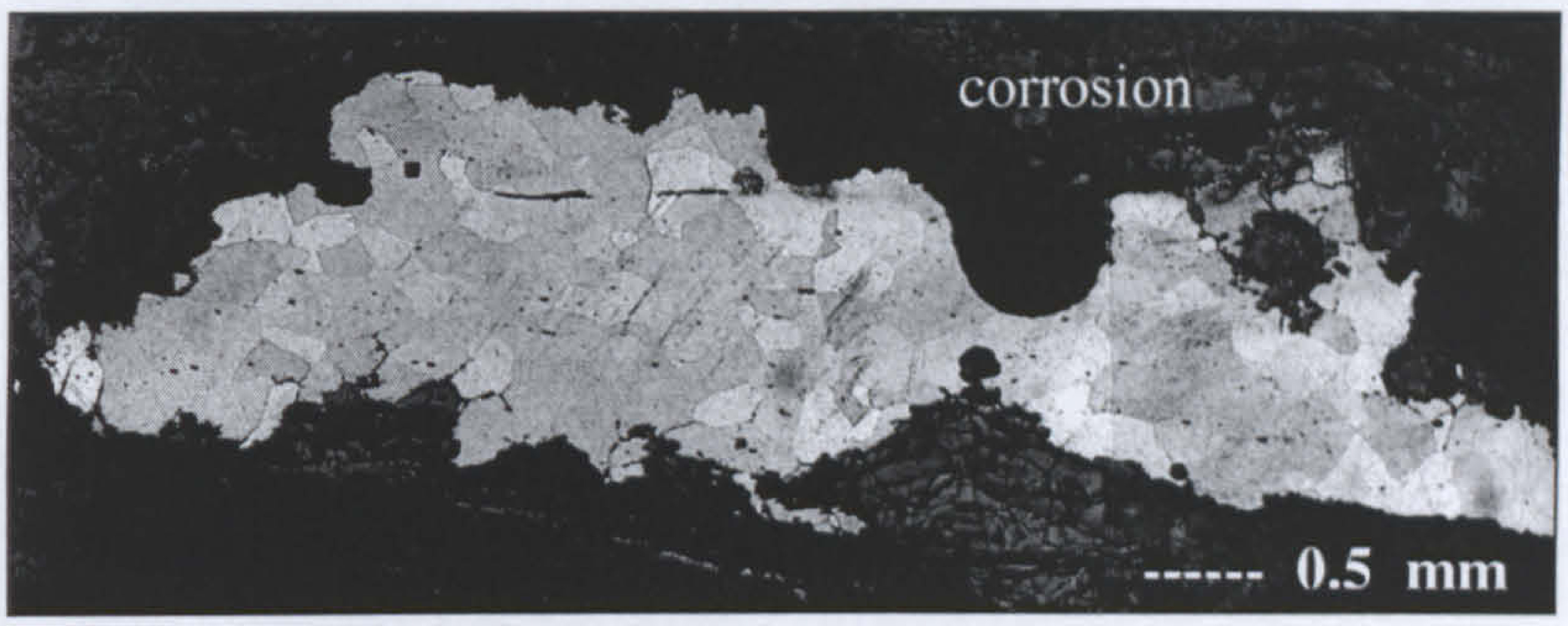


Figure 117b: Detail.

This sabre, with a small guard and curved suspension point, is similar to another north Caucasus sabre number 712 h discussed by Nicolle (1999, 278). The style is found on Turkish sabres and is a common Central Asian style.

The sample taken from this sabre is mostly corroded with only this island of ferrite grains visible. The sabre probably had a carburized edge which has corroded away.

KIS #14

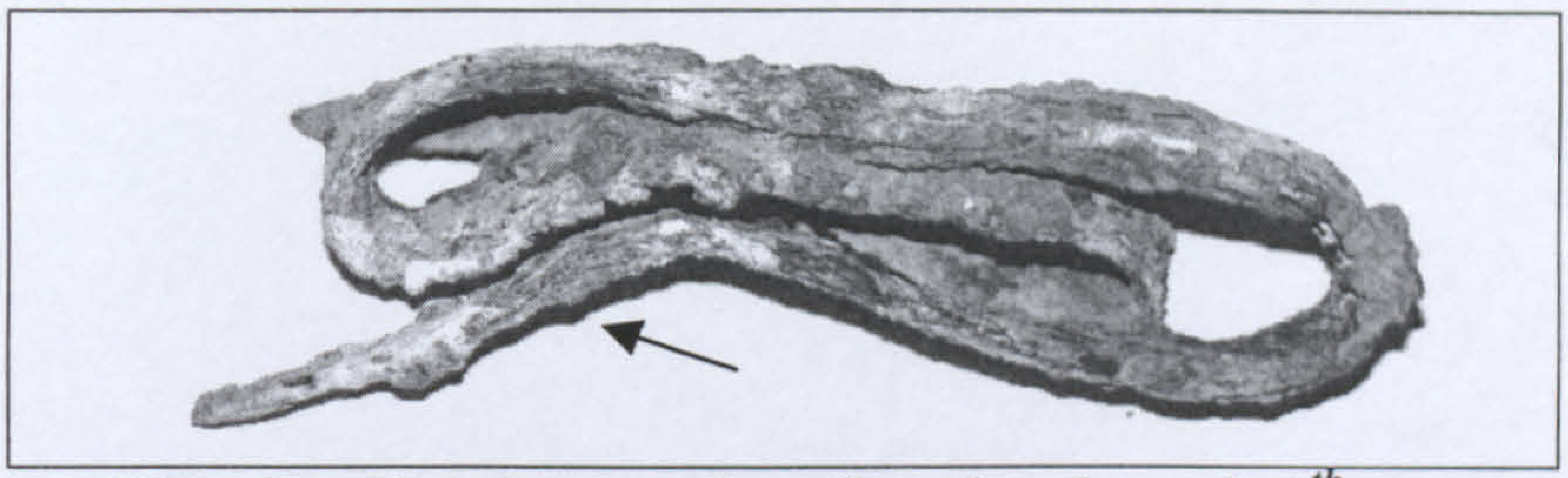


Figure 118a: Double edge sword attributed to the early 8^{th} century AD.

KIS #	Location	Length	Width	VH	Microstructure
14	Lermontovskaya 2	~ 87 cm	4 cm	102	Ferrite grains

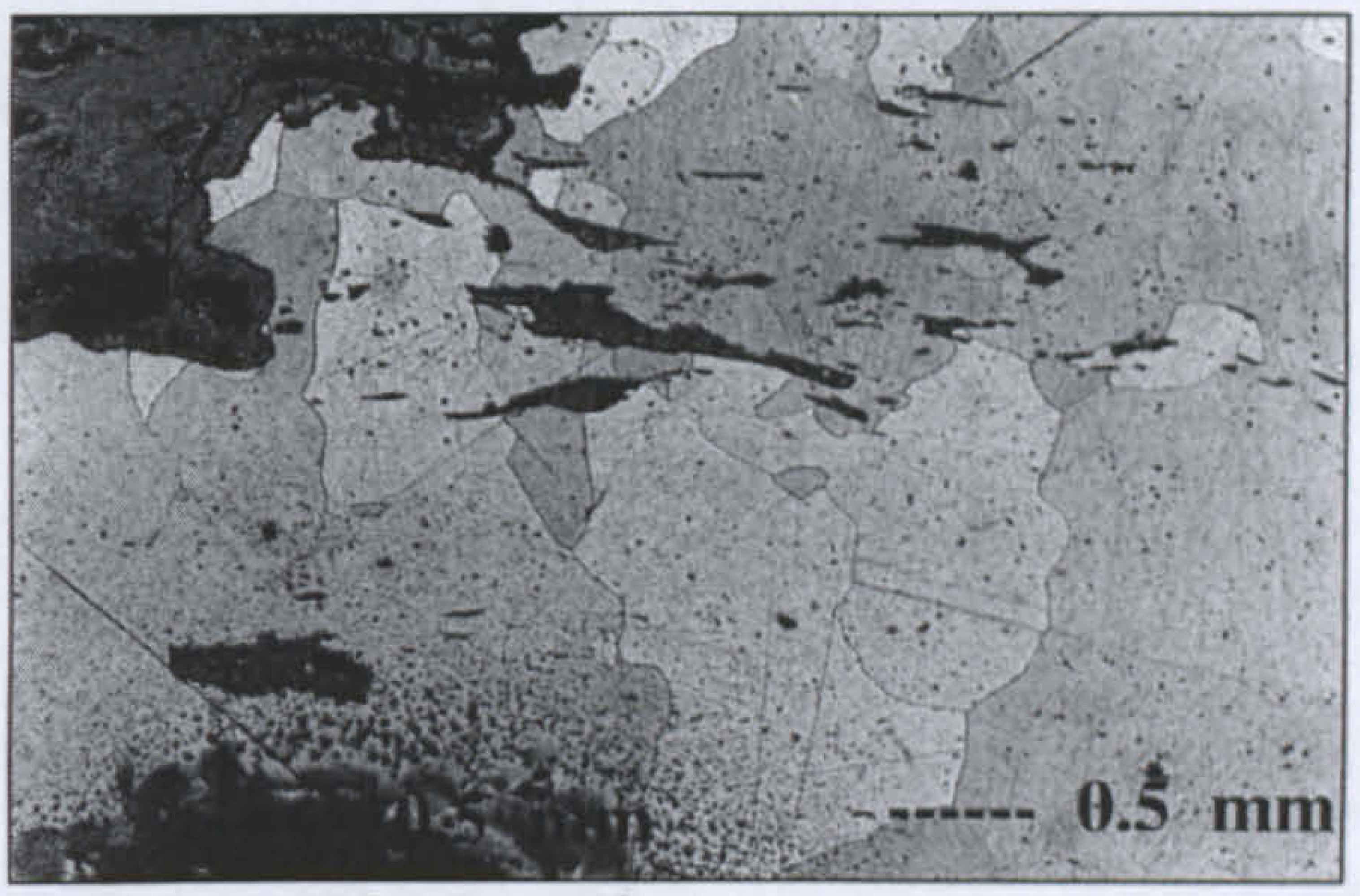


Figure 118b: Detail.

This sword was purposefully bent before being placed in the burial, suggesting a ritual practice of "killing" the sword, also see sample JUM # 8. The microstructure reveals relatively large grains of ferrite, some about ½ millimetre across. The dark elongated areas are corrosion.

JUM # 5

Figure 119a: Sabre.

JUM #	Length	Width	Thickness	Microstructure
5	87 cm	3.5 cm	0.5 cm	Ferrite grains, elongated slag inclusions and etch pits

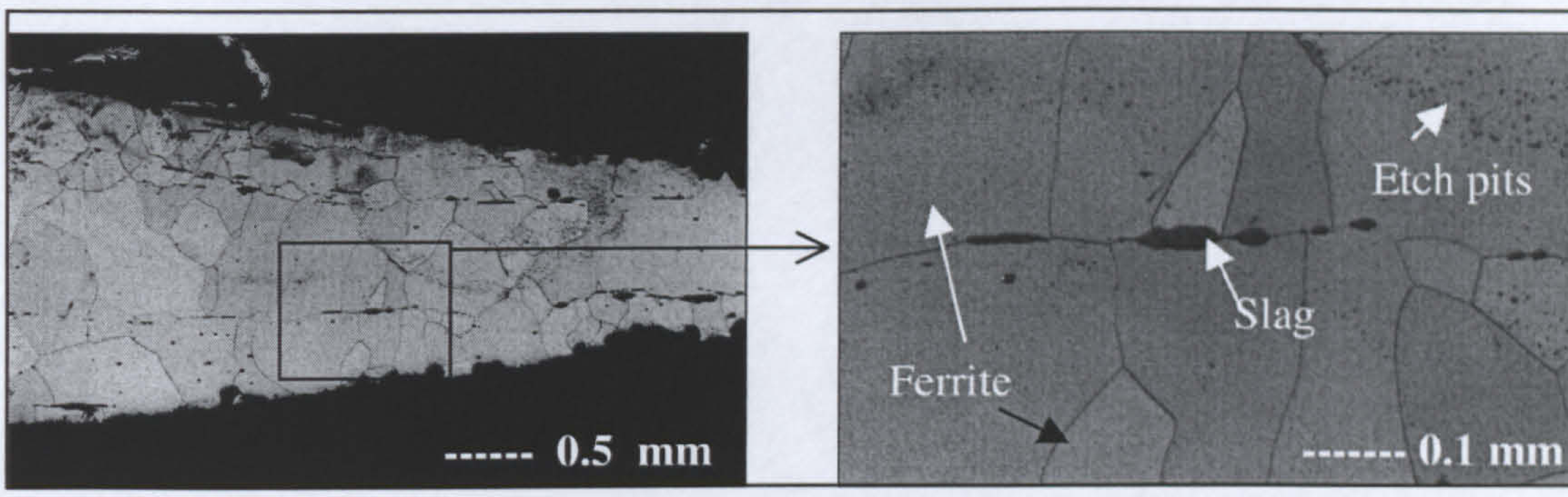


Figure 119b: Detail.

The sabre has a small guard near the handle. The handle is a modern reconstruction.

The area sectioned is mainly composed of ferrite. A broken line of elongated slag inclusions can be observed through the section, from left to right. If there had been a carburised edge, it has completely corroded in this sample. The edge of the blade and the tip were probably made of steel although no evidence remains. The small dark spherical spots are etch pits which are associated with precipitates of carbides or nitrides (see Samuels, 1980, 69). Etch pits are found in quenched ferrous products suggesting that the sabre was quenched, further supporting the belief that it probably had a carburized edge.

JUM # 10

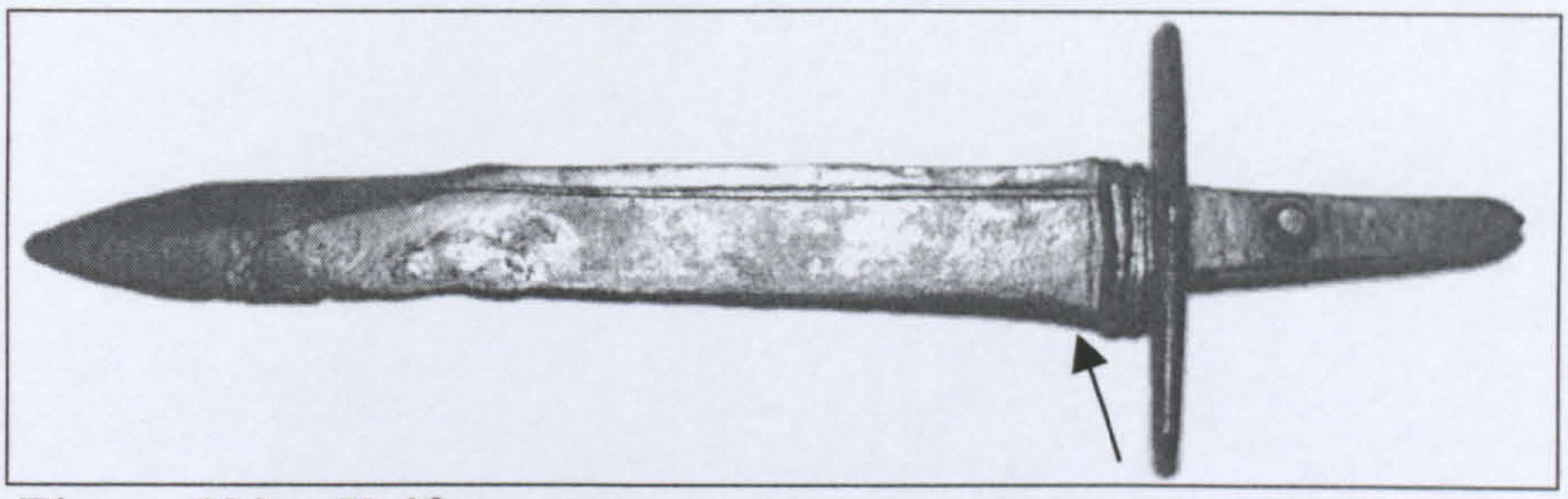


Figure 120a: Knife.

JUM #	Length	Microstructure
10	16 cm	Remains of ferrite

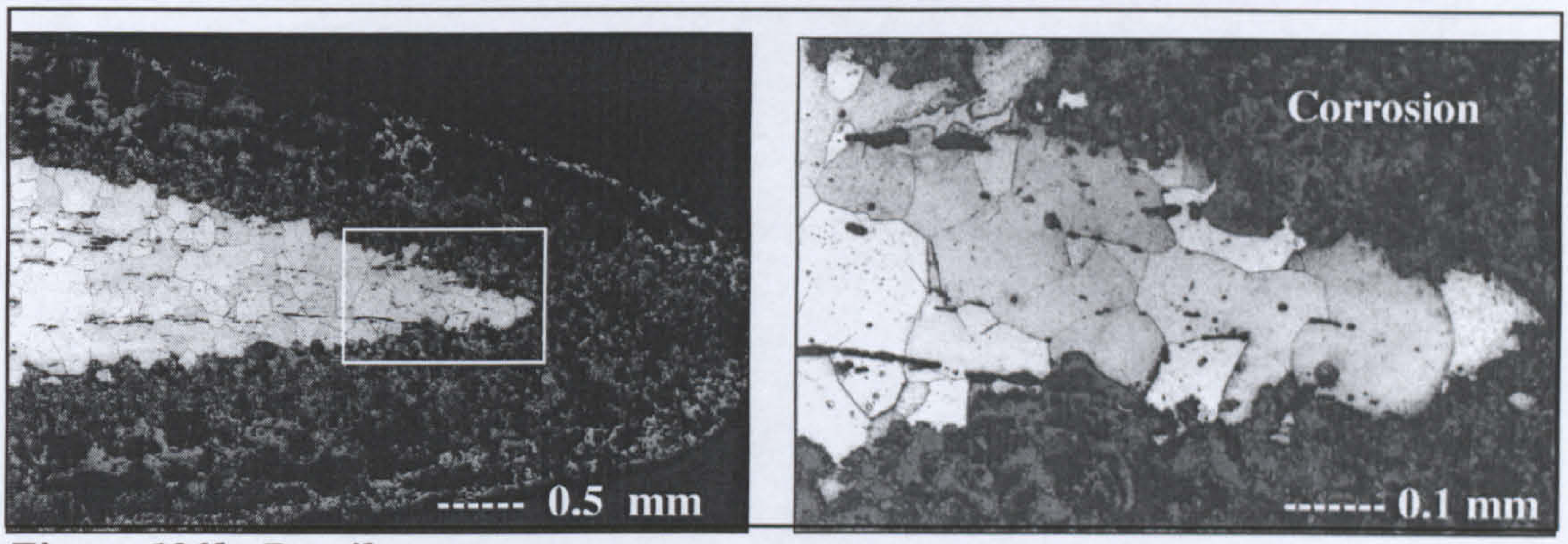


Figure 120b: Detail.

The microstructure is composed of ferrite with a relatively even outer crust of corrosion. A string of elongated slag inclusions runs along the sample. The tip and edge near the tip was probably made of steel although no evidence for this has been preserved.

JUM # 11

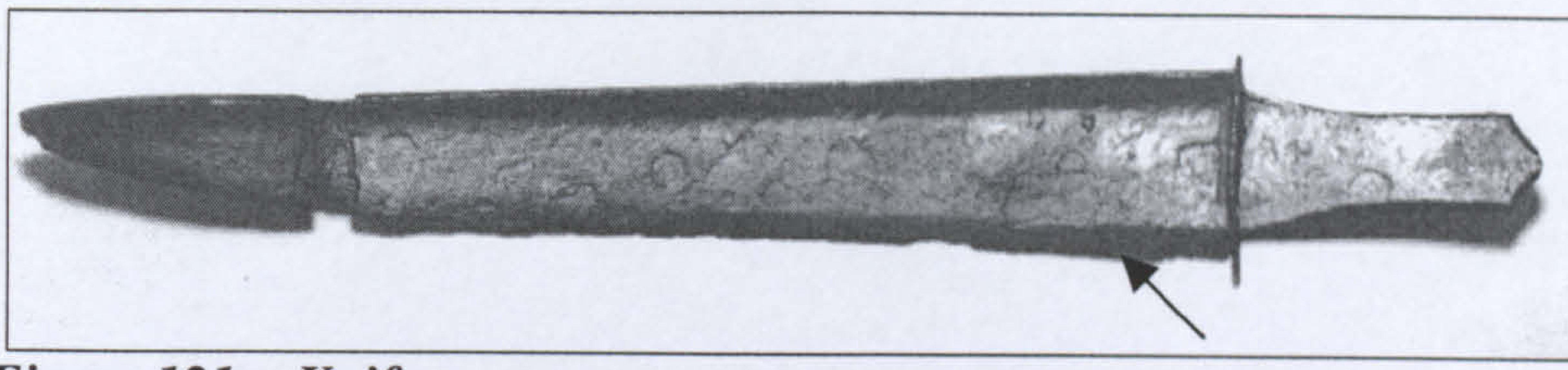


Figure 121a: Knife

JUM #	Length	Microstructure
11	15 cm	Ferrite grains in centre with quenched low carbon edge

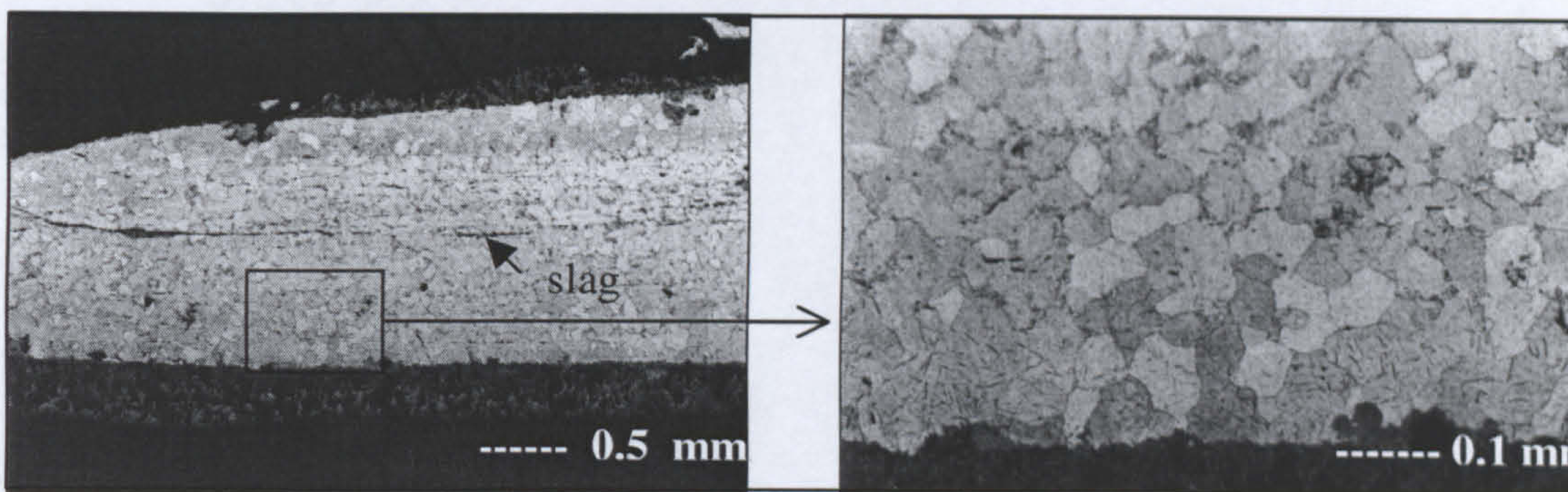


Figure 121b: Detail.

The knife is associated with the Alani culture. The back edge of the knife is raised and flattened, whereas the cutting edge has a sharp angle down to the cutting surface.

A line of elongated slag inclusions can be observed in the centre of the blade surrounded by ferrite grains. The microstructure suggests that the knife was made of two pieces of iron forge welded together. The sides of the blade appear to have lathes within the ferrite grains suggesting that the edge is composed of a low carbon iron that appears to have been quenched.

JUM #12

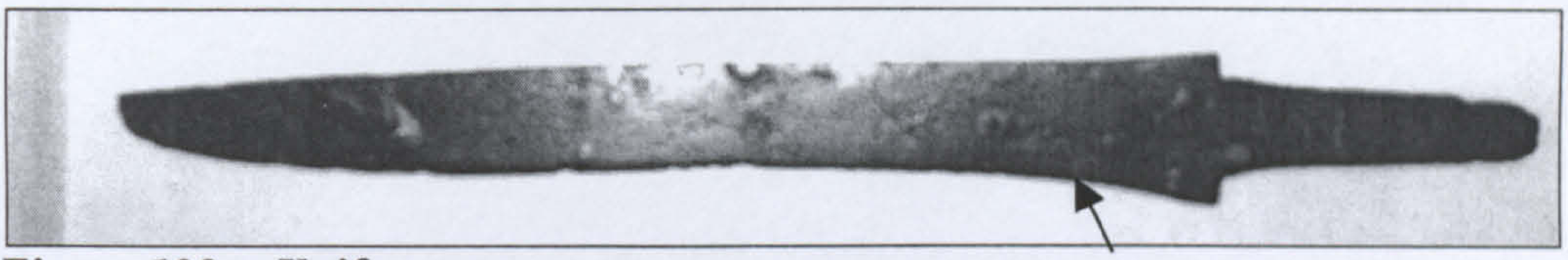


Figure 122a: Knife.

JUM #	Length	Microstructure
12	20 cm	Ferrite grains with occasional intergranular pearlite

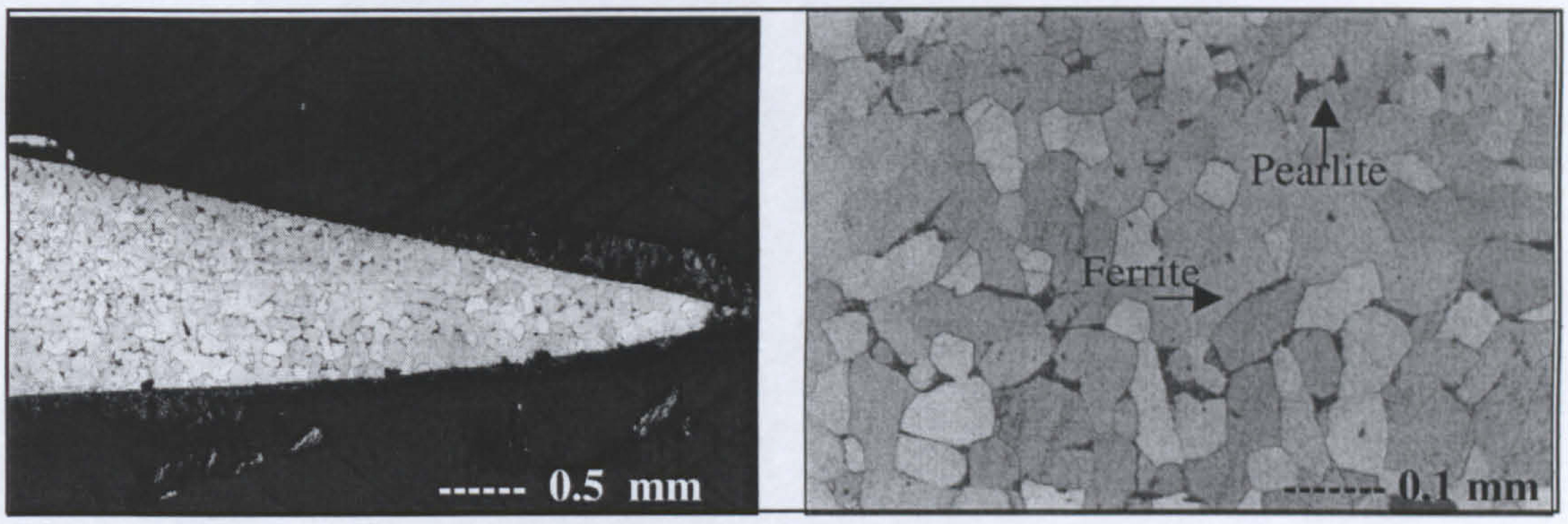


Figure 122b: Detail.

The knife is composed of a single piece of low carbon iron. The microstructure is primarily composed of grains of ferrite with occasional intergranular pearlite, which appears as dark areas between the lighter ferrite grains. The sample is virtually free from slag and non-metallic inclusions.

JUM # 13

Figure 123a: Knife.

JUM #	Length
13	22 cm

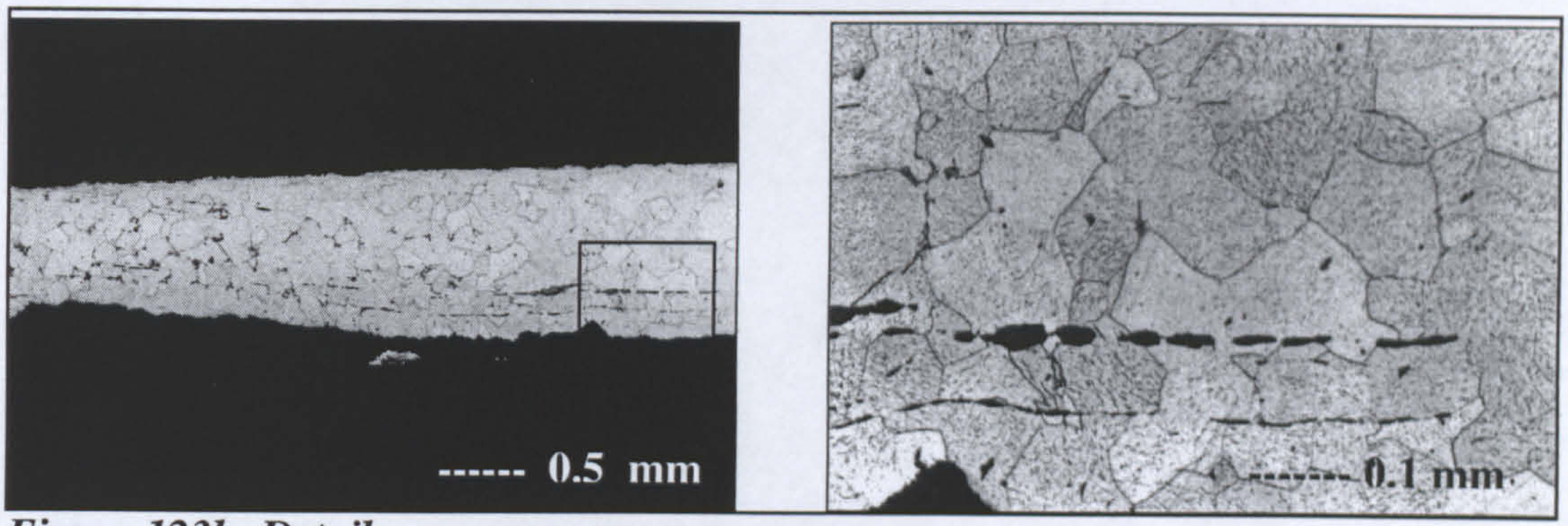


Figure 123b: Detail

The knife contains elongated slag stringers in a ferritic matrix. It appears to have carbide or nitride etch pits, which according to Samuels (1980, 69) often appear in quenched ferrous objects.

JUM # 16

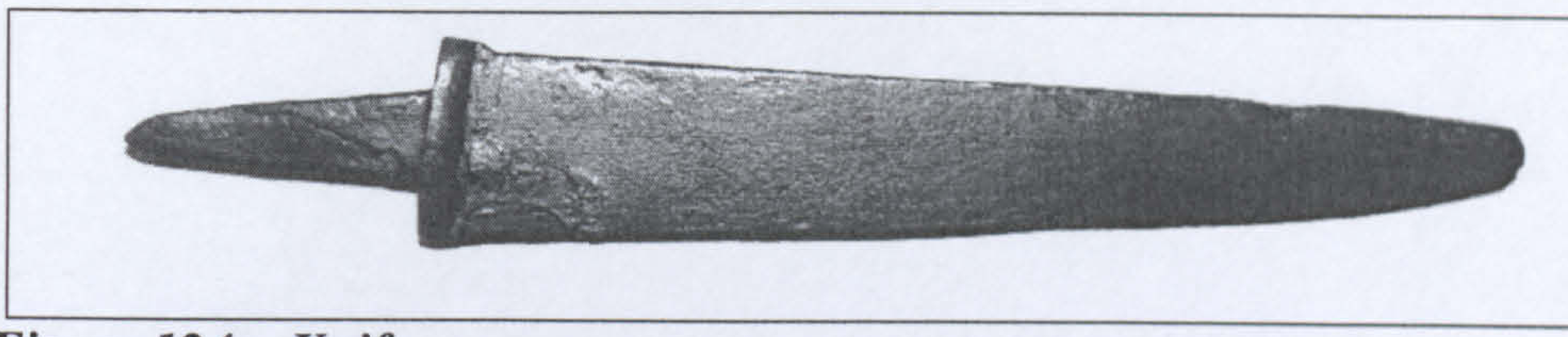


Figure 124a: Knife.

JUM #	Length
16	14 cm

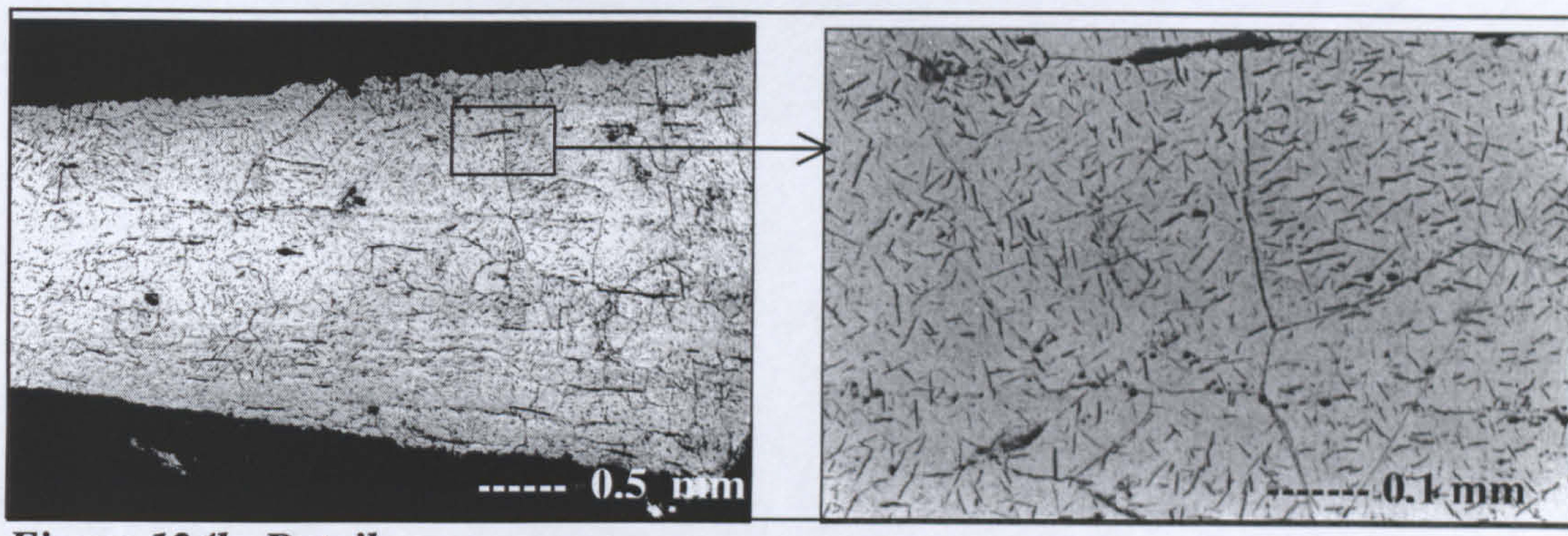


Figure 124b: Detail.

The blade seems to be composed of iron and elongated slag inclusion. The blade appear to have lathes within the ferrite grains suggesting that it is composed of a low carbon iron that appears to have been quenched.

KIS # 3

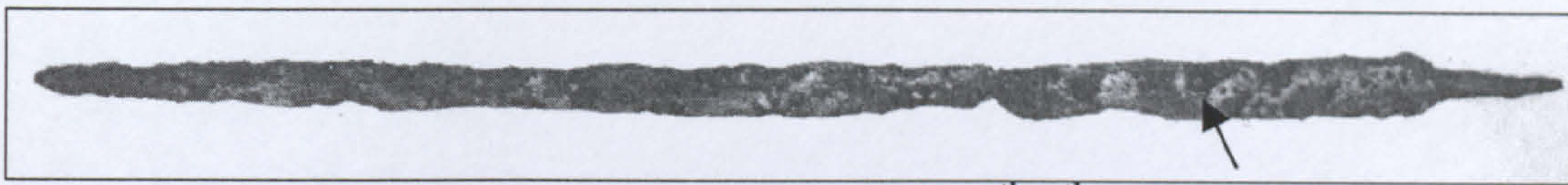


Figure 125a: Double edged sword attributed to the 4th-5th century AD.

Kis #	Location	Length	Width	Microstructure
3	Visokogorny	78 cm	3 cm	Carburized

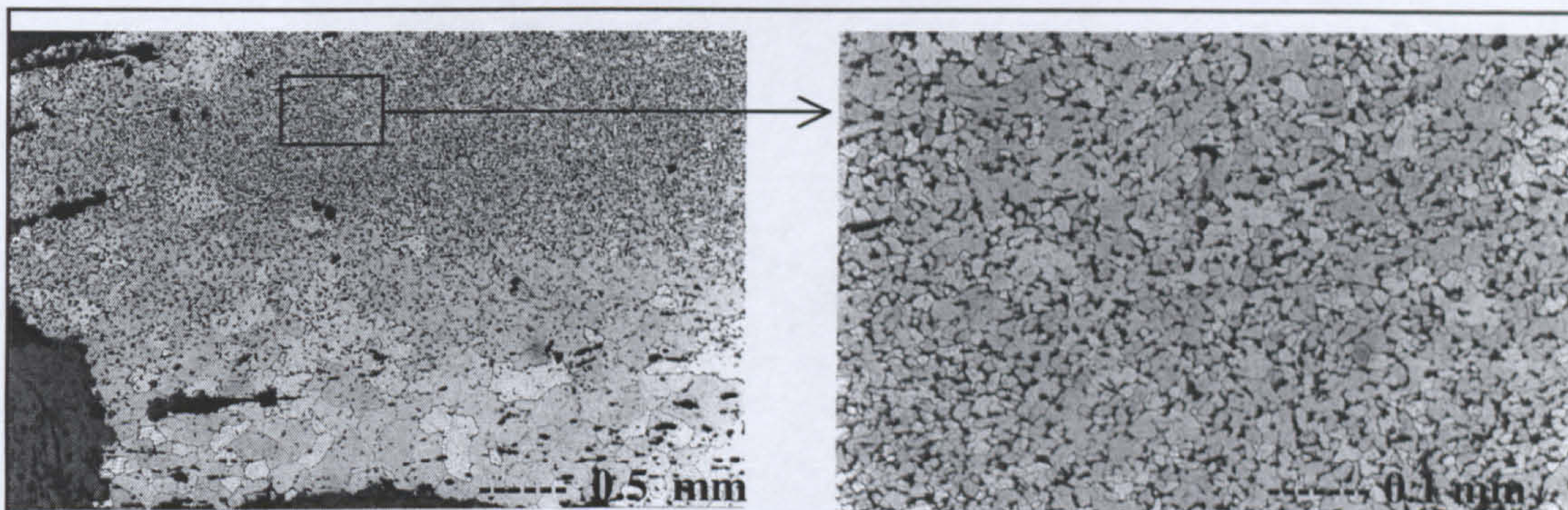


Figure 125b: Detail.

This double-edged sword was probably of European origin, however, this type of sword was also used in Central Asia. It probably originally had a guard which has not survived.

The microstructure indicates that the sword is composed of carburised iron that was quenched. Comparatively large grains of ferrite can be observed in the centre of the blade, corresponding to the bottom of figure 125b (left). The presence of intergranular pearlite, indicating higher carbon areas, can be seen at the top of figure 125b (left), corresponding to the edge of the blade. The gradual increase of carbon from the ferritic centre of the blade, to the higher carbon edge indicates a carburisation process.

KIS # 8

Figure 126a: Sabre perhaps from the 11th century AD.

Kis #	Location	Length	Width	Thickness	VH	Microstructure
8	Rim Gora	65 cm	3 cm	0.7 cm	473	Tempered and Plate Martensite

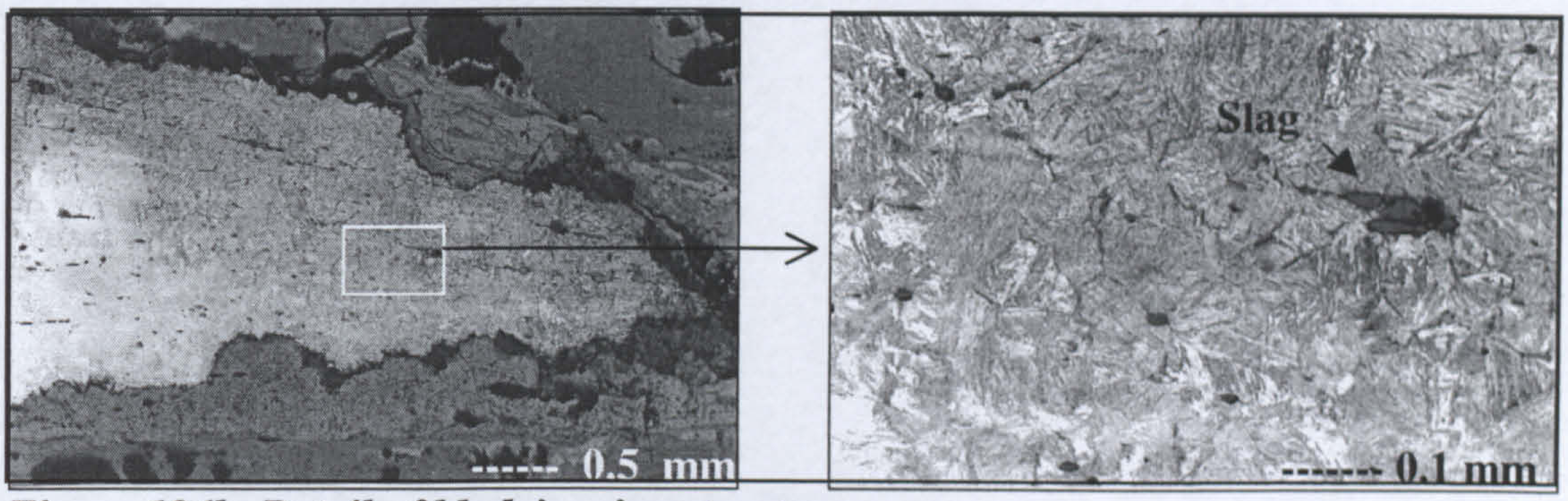


Figure 126b: Detail of blade's microstructure

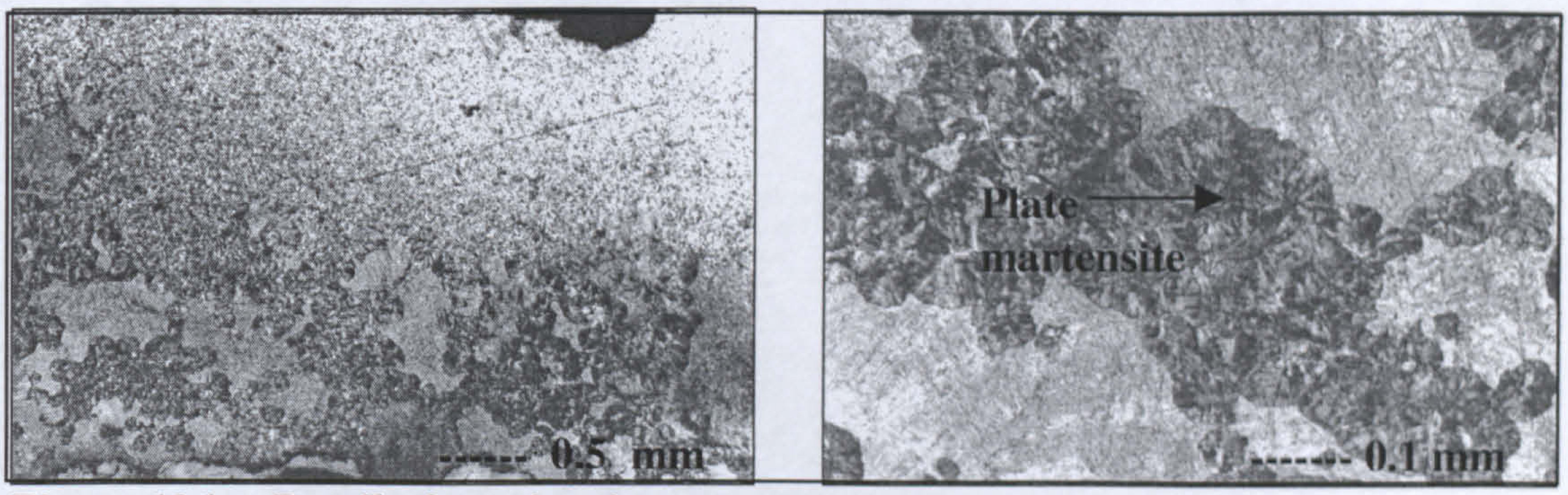


Figure 126 c: Detail of tang's microstructure

The sabre is attributed to the late Alan-Turkic culture. The sabre is made of carburised iron, which was quench hardened and tempered producing lath martensite in the blade and plate martensite on the tang. Elongated slag inclusions and other non-metallic inclusions were observed in the microstructure. The blade would have been very hard but brittle. During the microhardness testing the martensite cracked.

KIS # 12

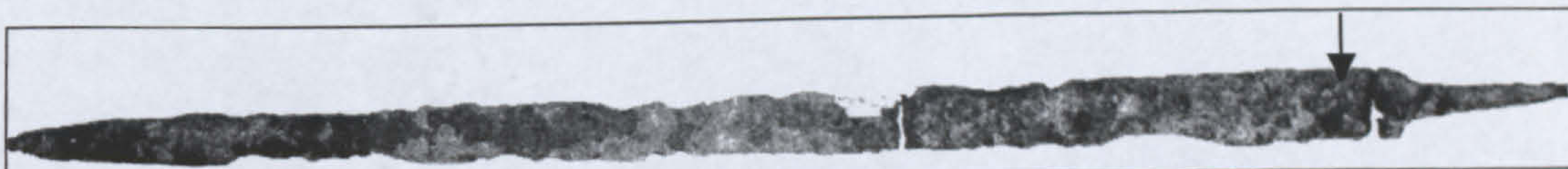


Figure 127a: Double edge sword attributed to the mid 1st millennium AD.

Kis #	Location	Length	Width	Microstructure
12	Near Kislovodsk	80 cm	3 cm near top 4 cm near base	Carburized

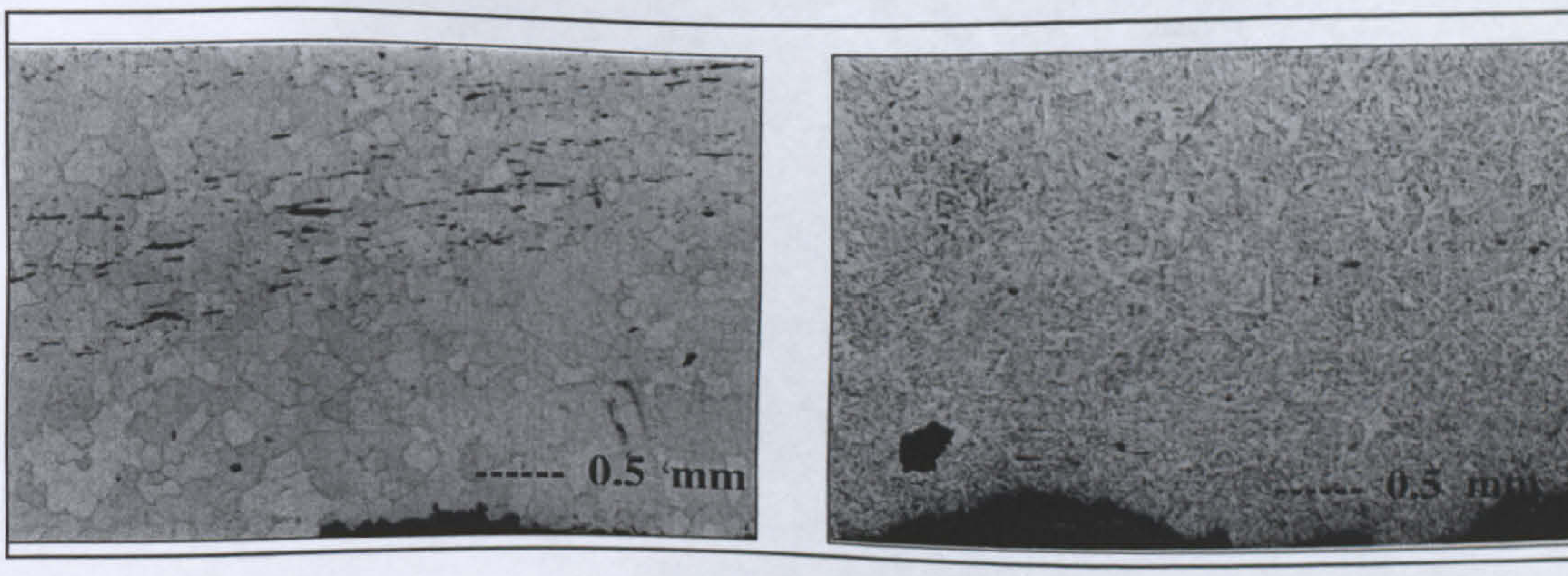


Figure 127 b: Detail.

The blade is primarily composed of large ferrite grains. The percentage of martensite increases towards the exterior indicating a carburized edge (figure 127b, right bottom).

KIS # 13

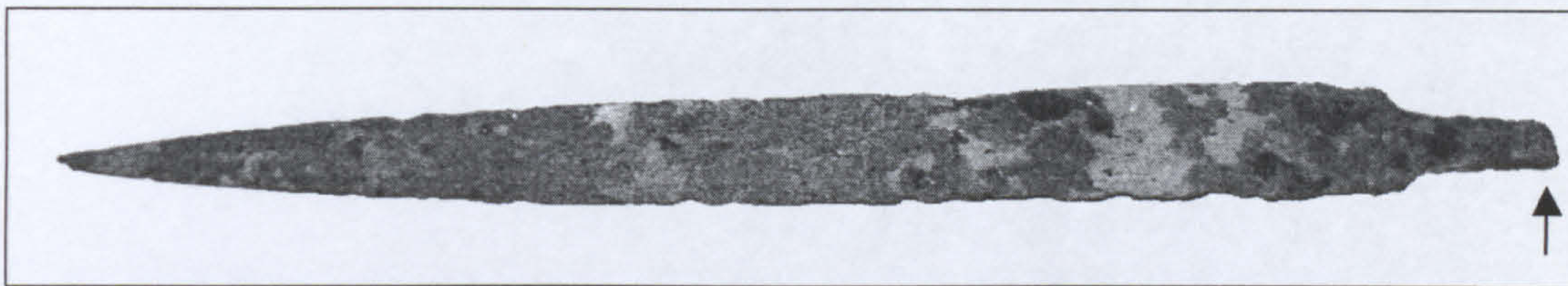


Figure 128a: Spearhead attributed to the mid 1st millennium AD.

Kis #	Location	Length	Width	Microstructure
13	Near Kislovodsk	39 cm	4 cm	Carburized

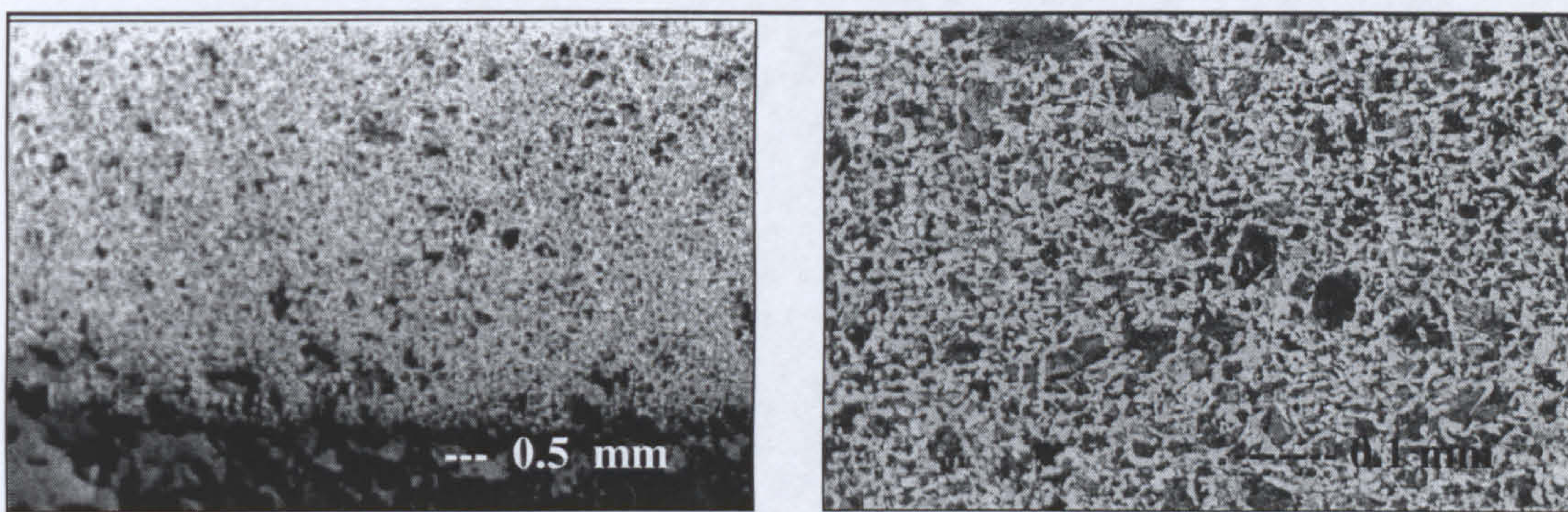


Figure 128 b: Detail.

The section was taken from the tang rather than the blade. The carbon content decreases toward the interior indicated by the decreasing amount of martensite from the edge to the centre signifying carburization.

KIS # 17

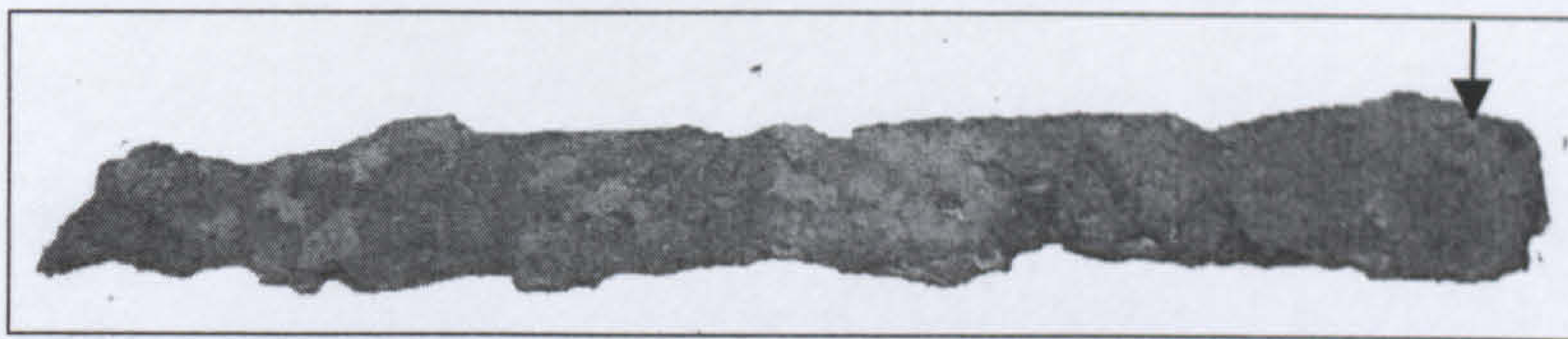


Figure 129a: Sword fragment attributed to the mid 1st Millennium AD.

Kis #	Location	Length	Width	VH	Microstructure
17	Near Kislovodsk	> 36 cm	4 cm	105 interior 315 edge	Carburized

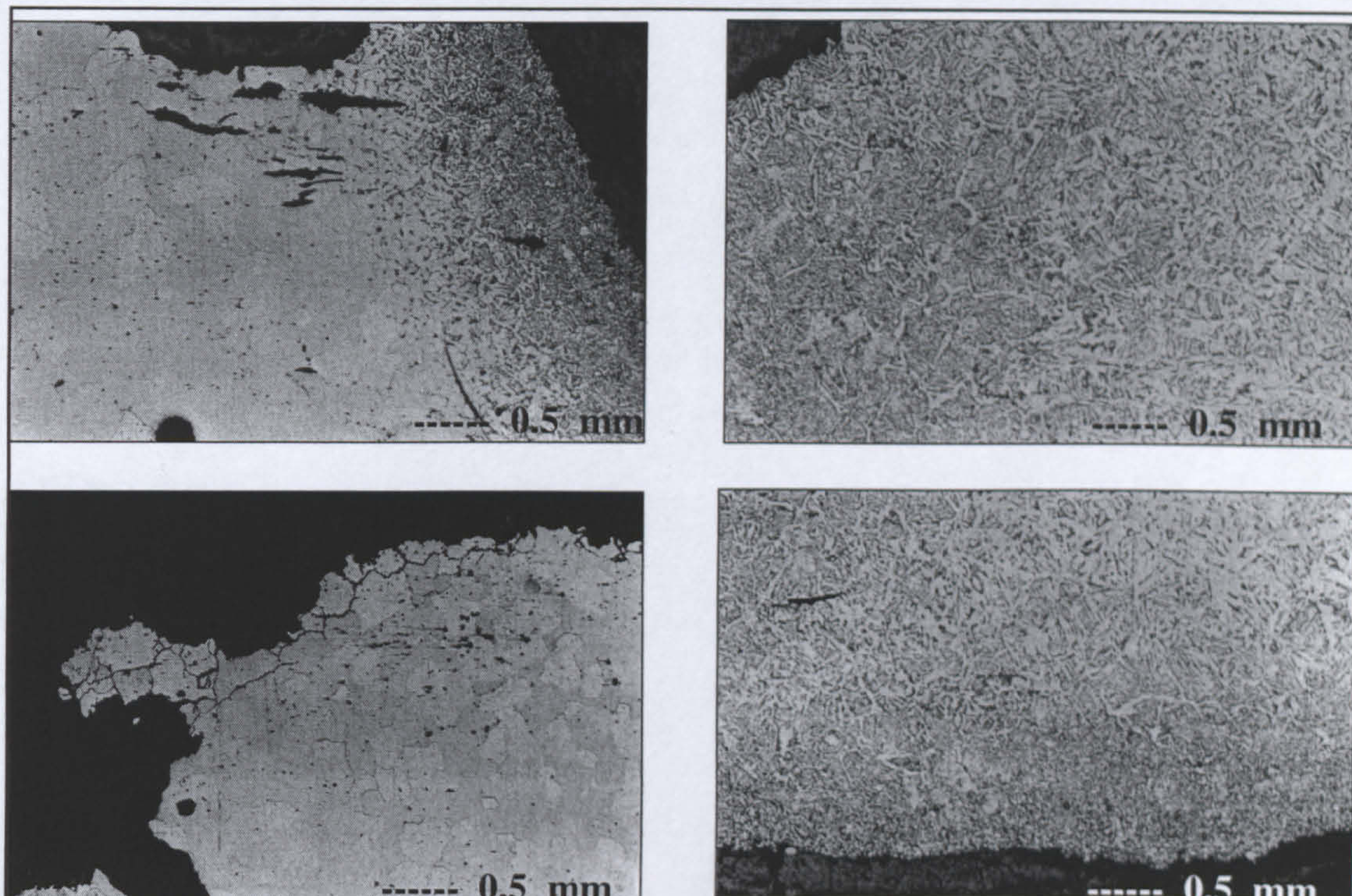


Figure 129b: Detail.

All that remains of this sword is a small fragment. The carbon content decreases toward the interior of the blade, indicated by the decreasing amount of martensite from the edge to the centre indicating a carburized blade that was subsequently quenched. The difference in hardness, from 105 VH in the ferrite region, to 315 VH near the edge, indicates a blade with a comparatively soft interior but containing a hard edge.

JUM #1

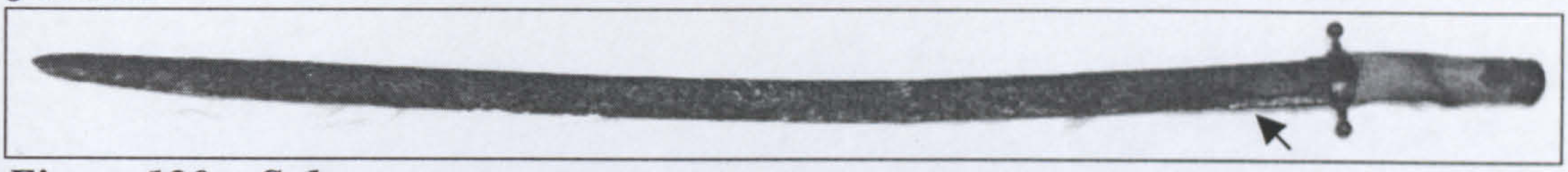


Figure 130a: Sabre

JUM #	Length	Width	Thickness	Microstructure
1	89 cm	3 cm	0.5 cm	Carburized

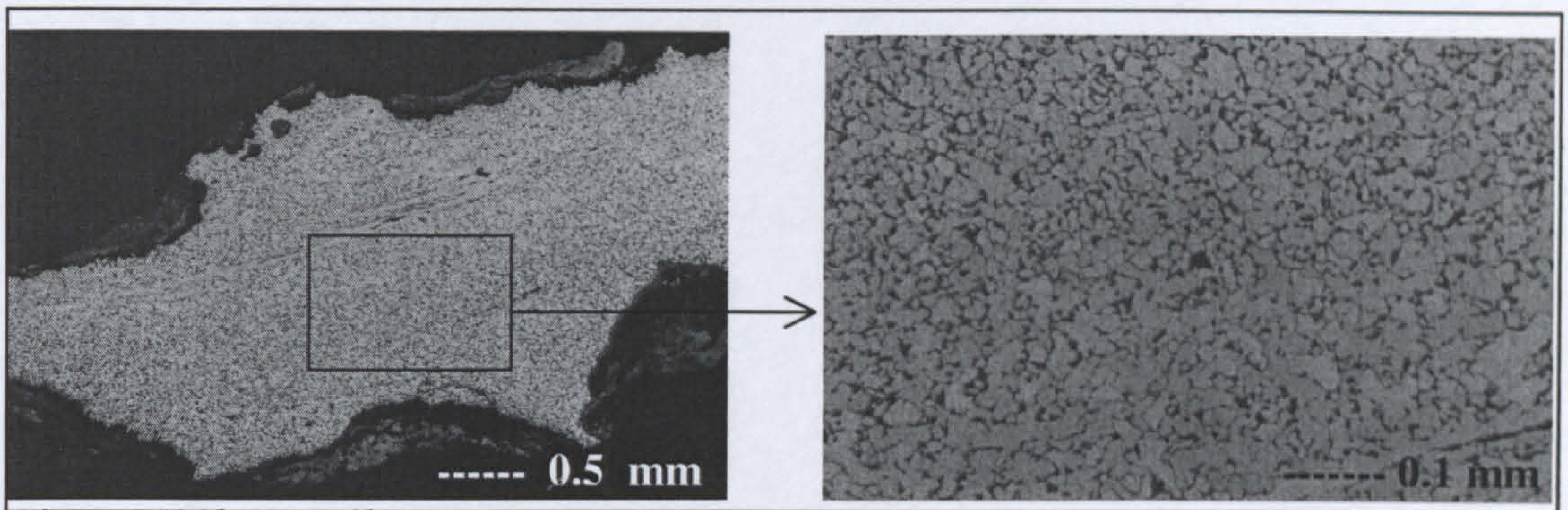


Figure 130b: Detail

The sabre has a small guard. The handle is a modern reconstruction.

The sample is composed completely of ferrite grains with intergranular pearlite indicating low carbon steel. The blade has a relatively homogenous carbon content and very few non-metallic inclusions indicating relatively clean steel, compared to the blades discussed above. This may be due to the location of the sample or the steel may have been from a carburized bloom.

JUM # 3

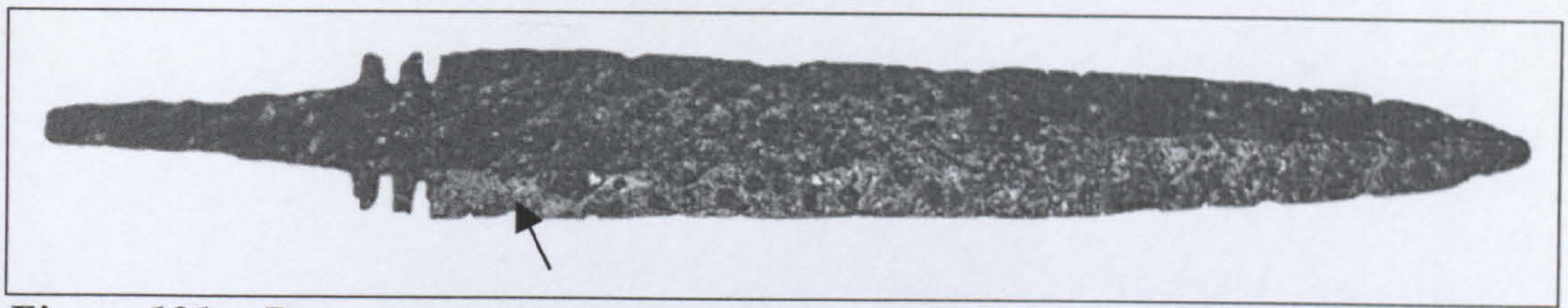


Figure 131a: Dagger.

JUM #	Length	Width	Microstructure
3	37 cm	4.5 cm at base	Carburised

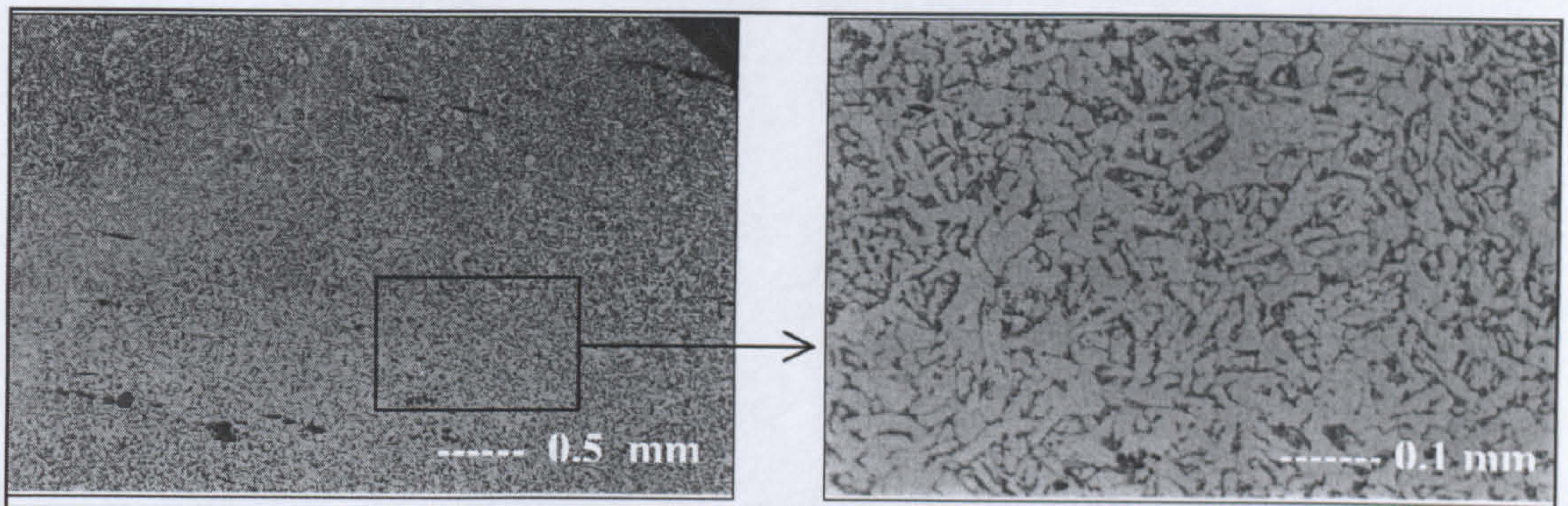


Figure 131b: Detail.

This sample from the dagger is composed of a relatively homogenous low carbon steel. Elongated slag inclusions are also present and distributed throughout the sample. The microstructure consists of ferrite with intergranular martensite. Whether the dagger was composed from a steely bloom or from a piece of carburised bloomery iron is uncertain.

JUM # 4

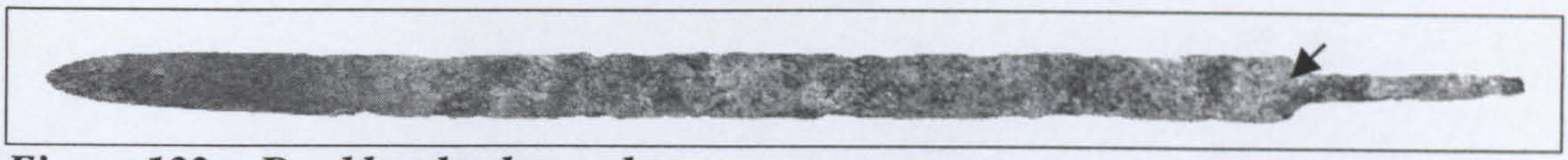


Figure 132a: Double edged sword.

JUM #	Length	Width	Microstructure
4	87 cm	4.5 cm	Carburized

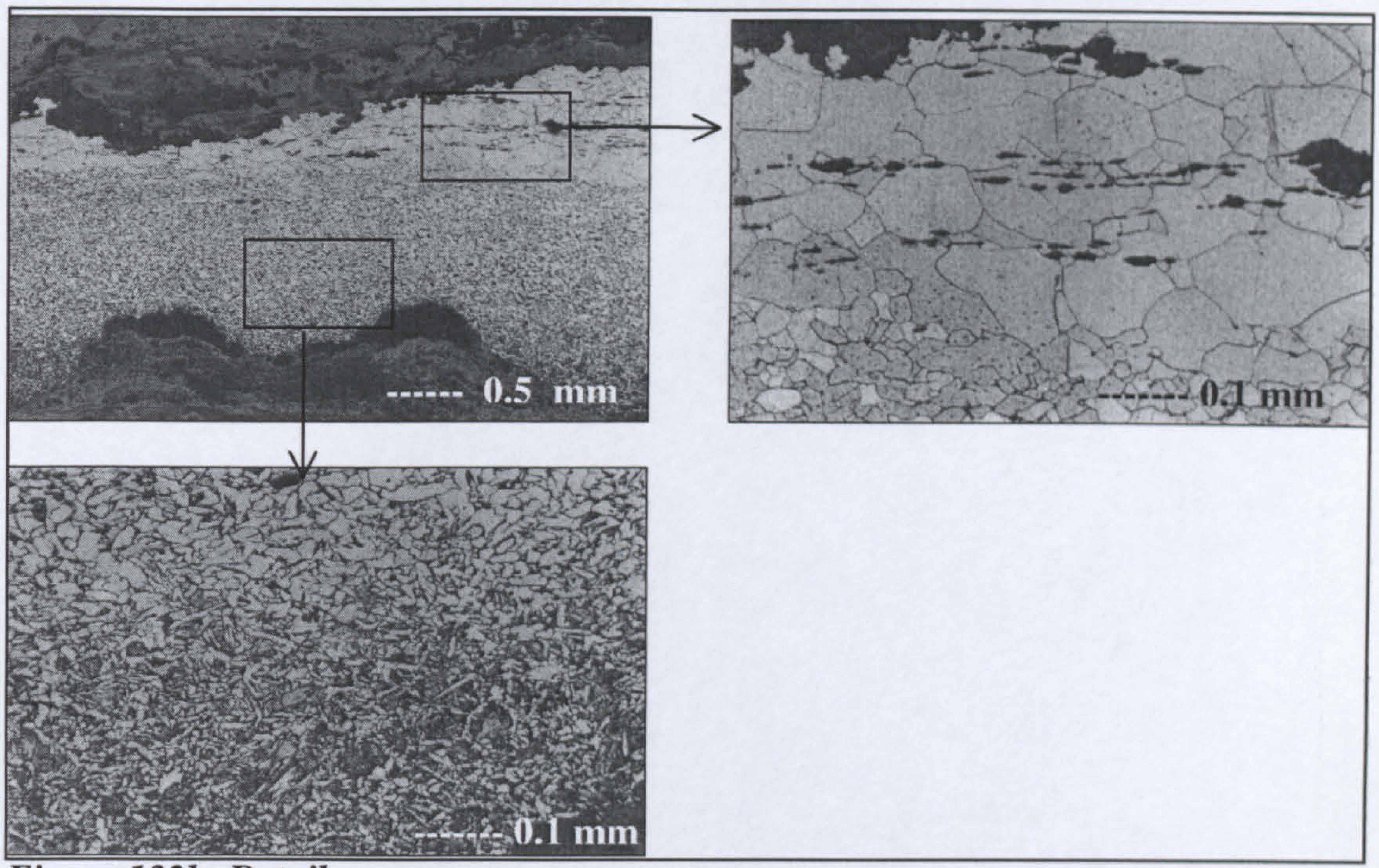


Figure 132b: Detail.

The centre of the blade is composed of large ferrite grains. The edge contains a higher percentage of ferrite towards the centre and more martensite towards the edge. There are also elongated slag stringers which appear in a higher concentration in the ferritic area.

JUM # 6

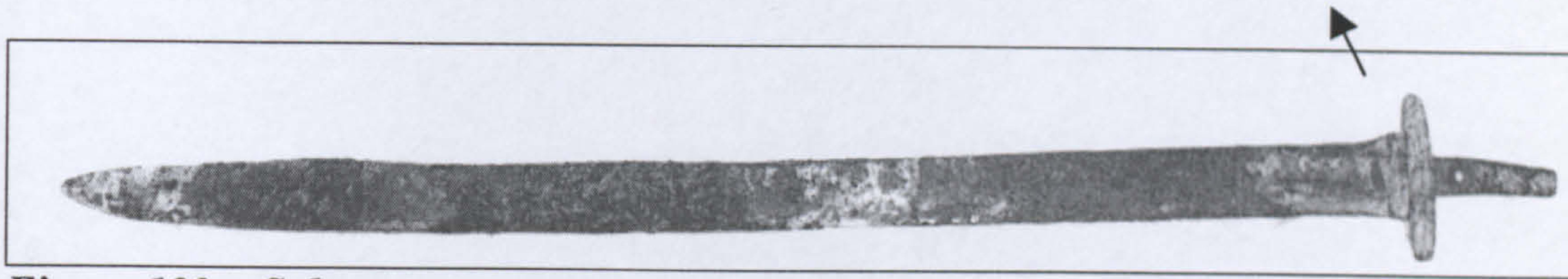


Figure 133a: Sabre

JUM #	Length	Width	Thickness	Microstructure
6	80 cm	3 cm	0.5 cm	Carburized

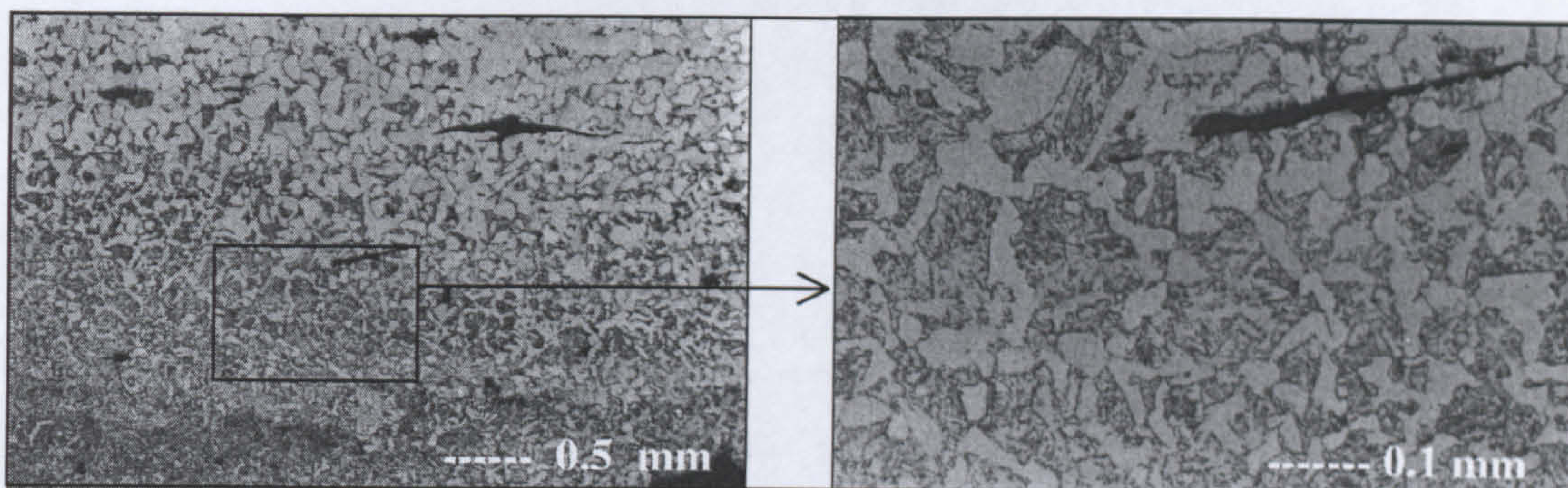


Figure 133b: Detail.

The sabre is composed of carburized steel. The edge contains more ferrite towards the centre and more martensite towards the edge. Non-metallic inclusions and elongated slag are spread throughout the sample. The elongated line in figure 133b (right) is a scratch on the polished section.

JUM # 18

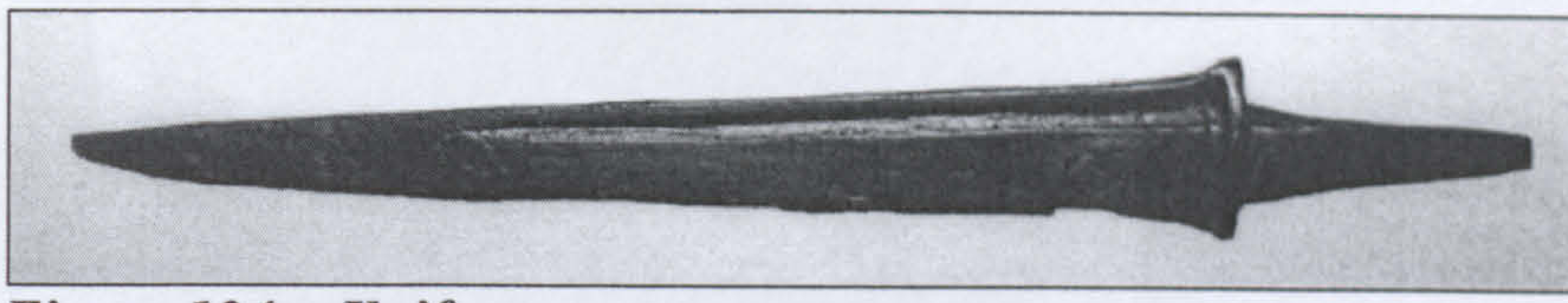


Figure 134a: Knife.

JUM #	Length	Microstructure
18	16 cm	Carburized

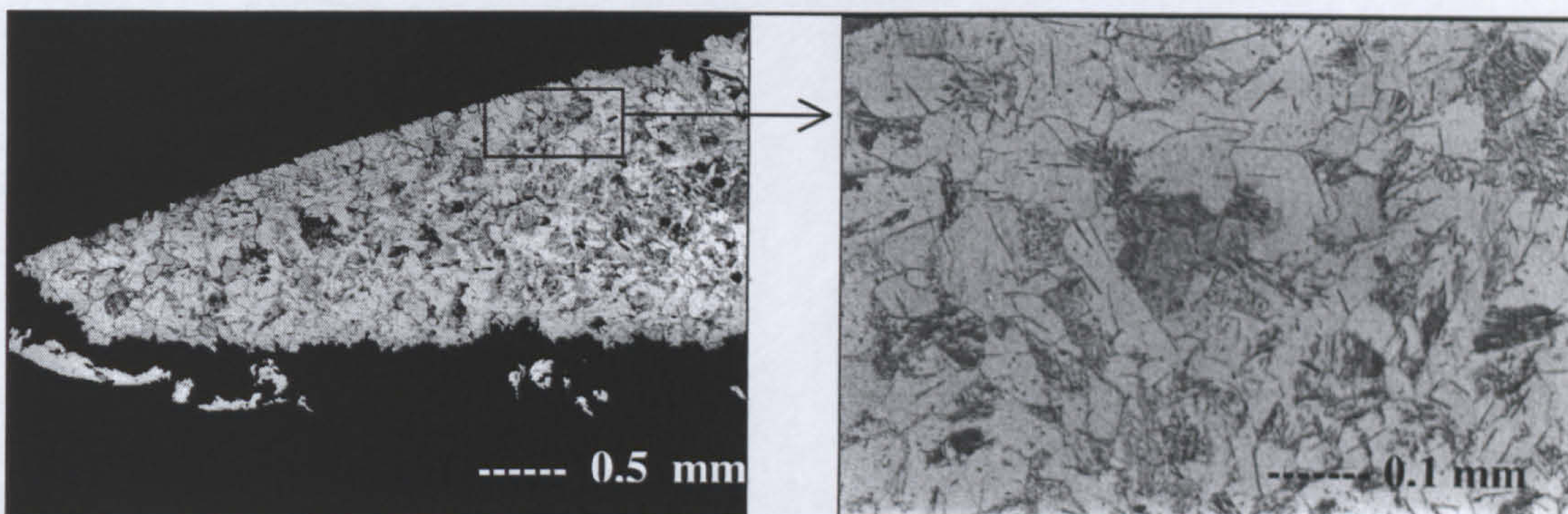


Figure 134b: Detail.

This knife is composed of quenched martensite and lower bainite. The small lines within the grains may be nucleation points (see Samuels, 1980, 329). The sample contains few non-metallic inclusions.

JUM # 19

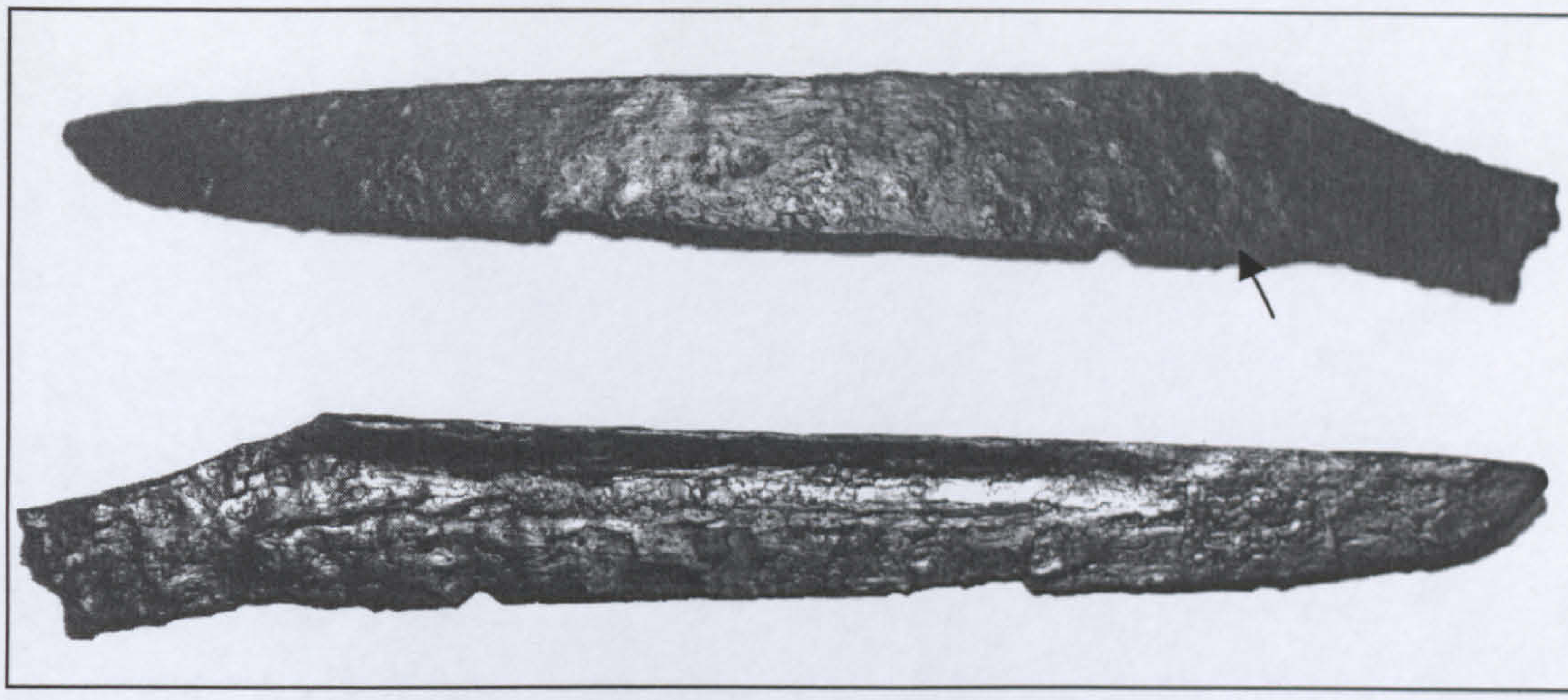


Figure 135a: Knife front and reverse.

JUM #	Length	Microstructure
19	18 cm	Ferrite and Martensite

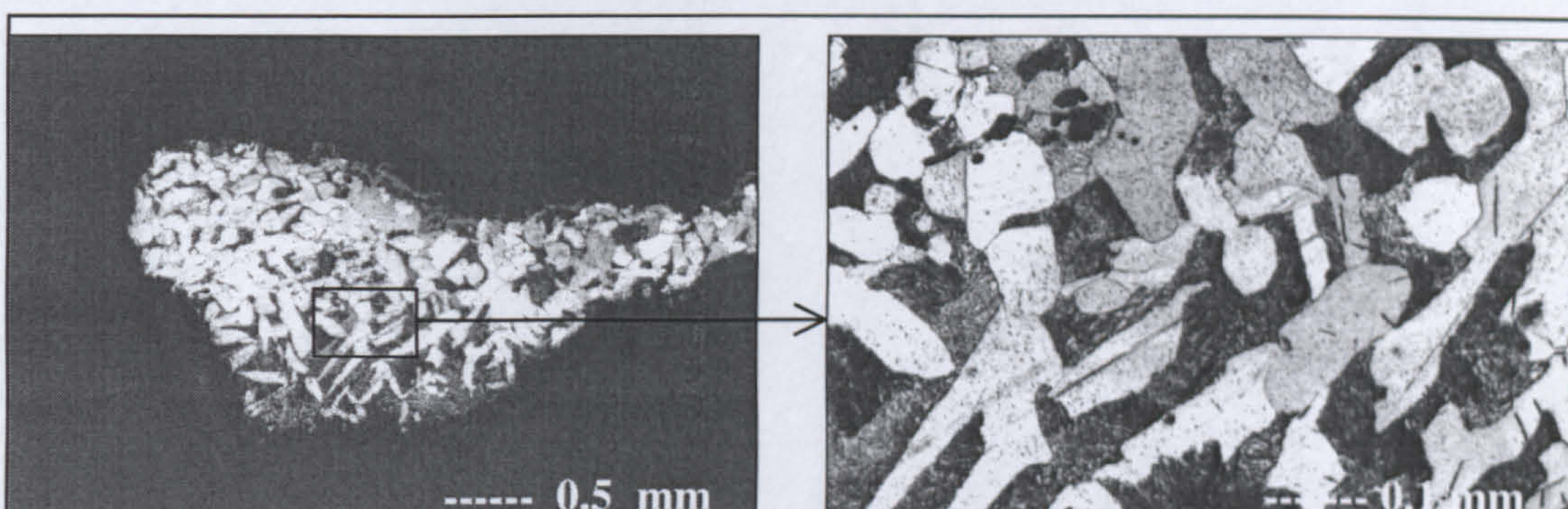


Figure 135b: Detail.

The knife has an interesting shape containing a depressed area on one side of the blade. The other side of the blade is flat.

The sample is virtually completely corroded however an island of uncorroded low carbon steel was observed. The microstructure reveals grains of ferrite with intergranular sorbite/pearlite.

KIS # 6

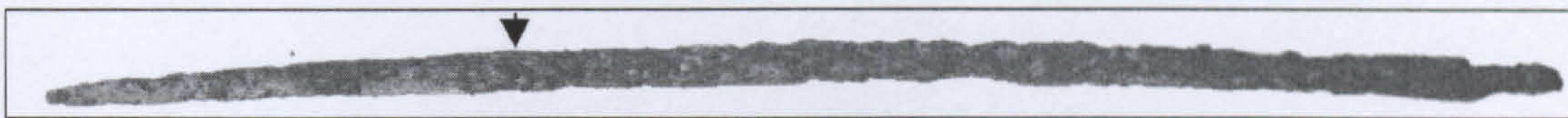
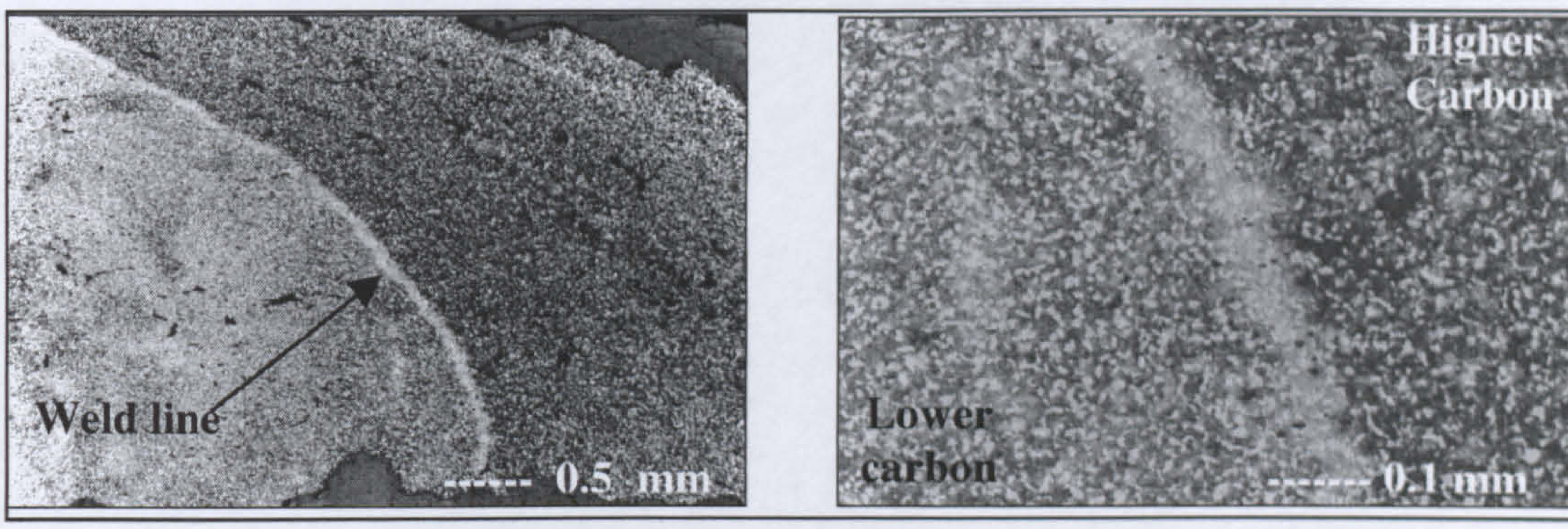


Figure 136a: Sabre attributed to the 10th – 12th century AD.

Kis #	Location	Length	Width	Thickness	Microstructure
6	Ooloo Dorbumly	77 cm	3 cm	0.5 cm	Forge-welded



The sabre had a higher carbon steel forge welded onto a lower carbon steel centre. The steel has few non-metallic inclusions.

KIS # 7

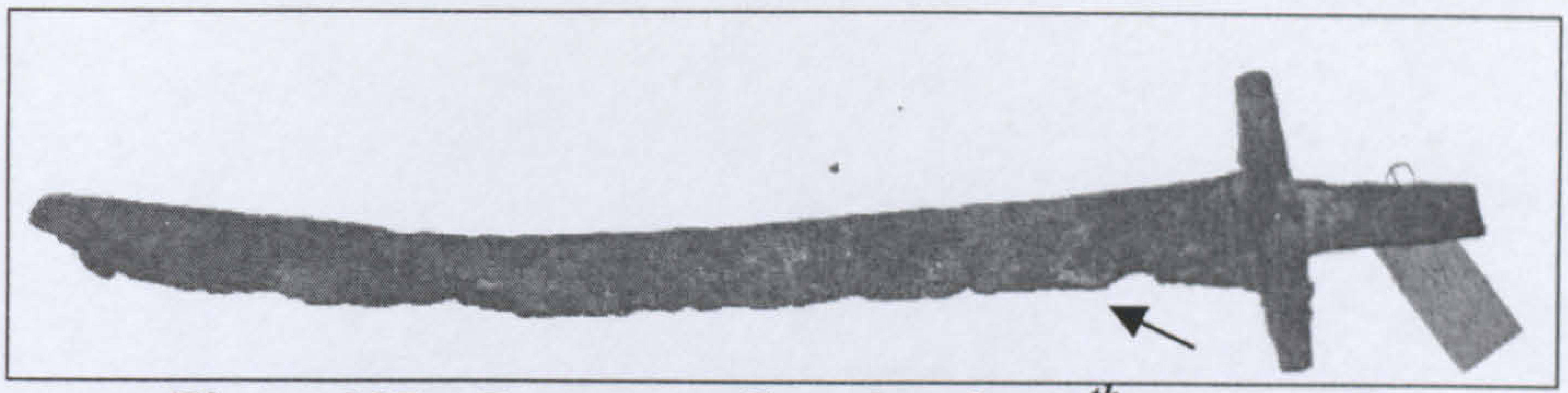


Figure 137a: Dagger attributed to the 11th century AD

Kis #	Location	Length	Width	Microstructure
7	Rim Gora	41 cm	2.5 cm	Forge welded

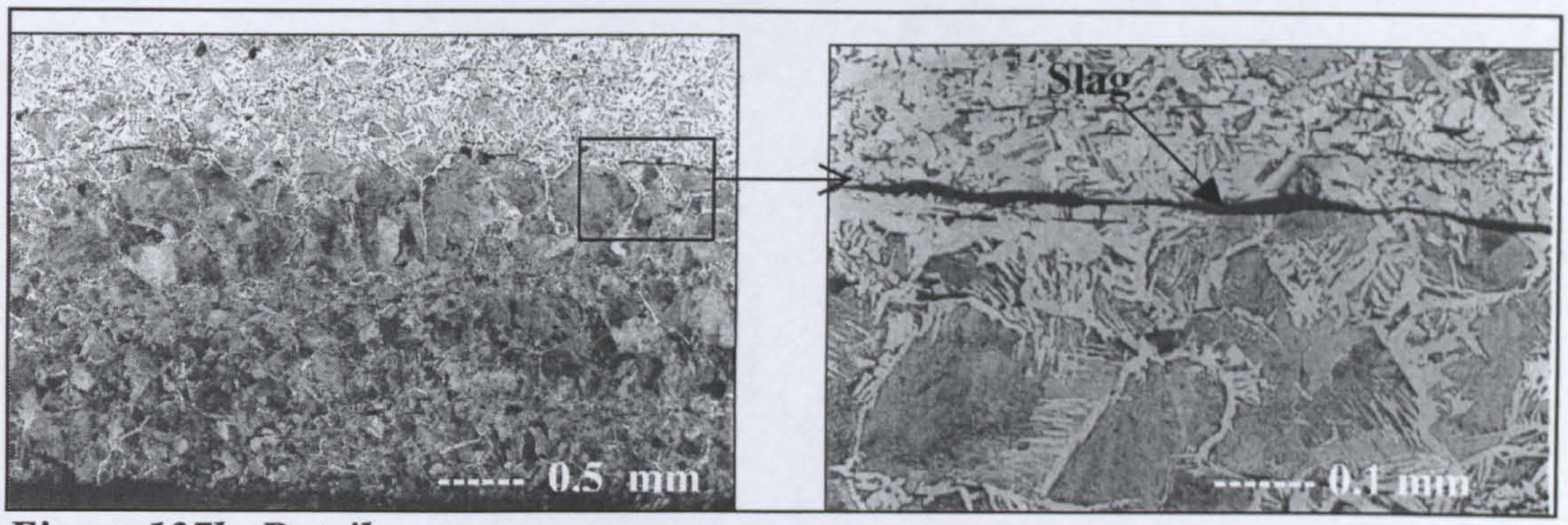


Figure 137b: Detail.

The dagger was probably made from a piece of a broken sabre, suggested by its odd "sabre like" shape. This sample is composed of at least two layers of forge-welded steel. An elongated slag inclusion is observed between the two layers. The area below the slag inclusion shows a rapidly cooled hypo-eutectoid (*c.* 0.5% C) steel with intergranular ferrite and Widmanstätten ferrite in a matrix of irresolvable pearlite.

JUM # 18

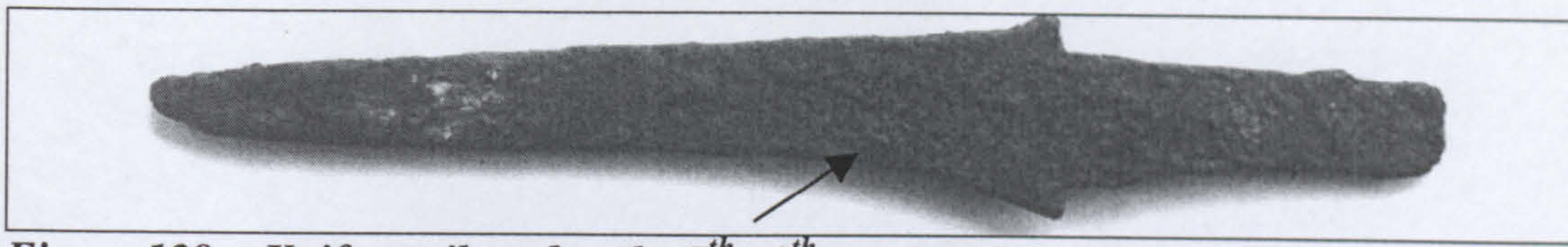


Figure 138a: Knife attributed to the 7th - 9th century AD.

Kis #	Location	Length	Width	Microstructure
18	Kislovodsk	11 cm	1.5 cm	Layered

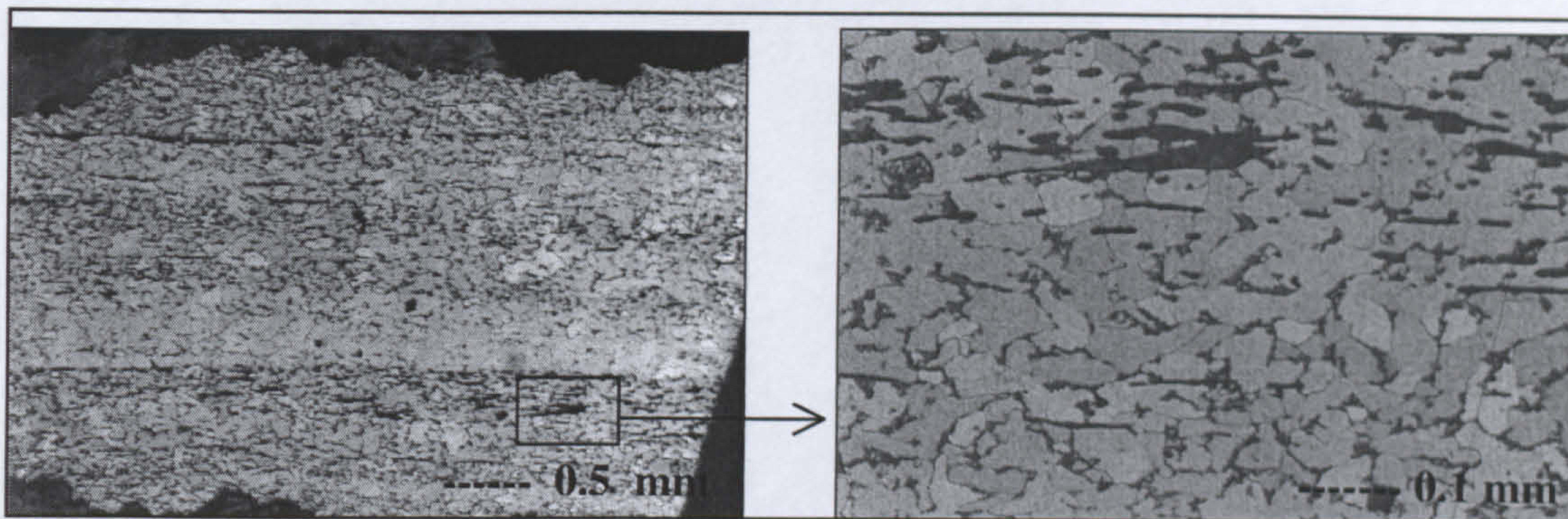


Figure 138b: Detail.

This knife shows the use of piling, alternative layers of higher and lower carbon iron were layered on top of each other and forged together. Slag inclusions can be seen along the weld joins.

JUM # 2

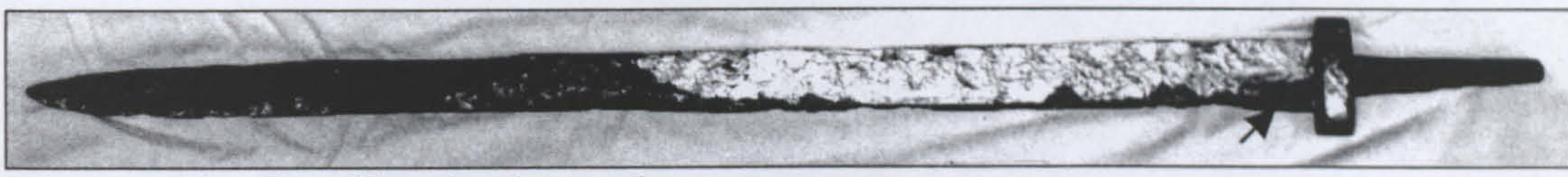


Figure 139a: Double edged sword.

JUM #	Length	Width	Thickness
2	59 cm	3 cm	0.5 cm

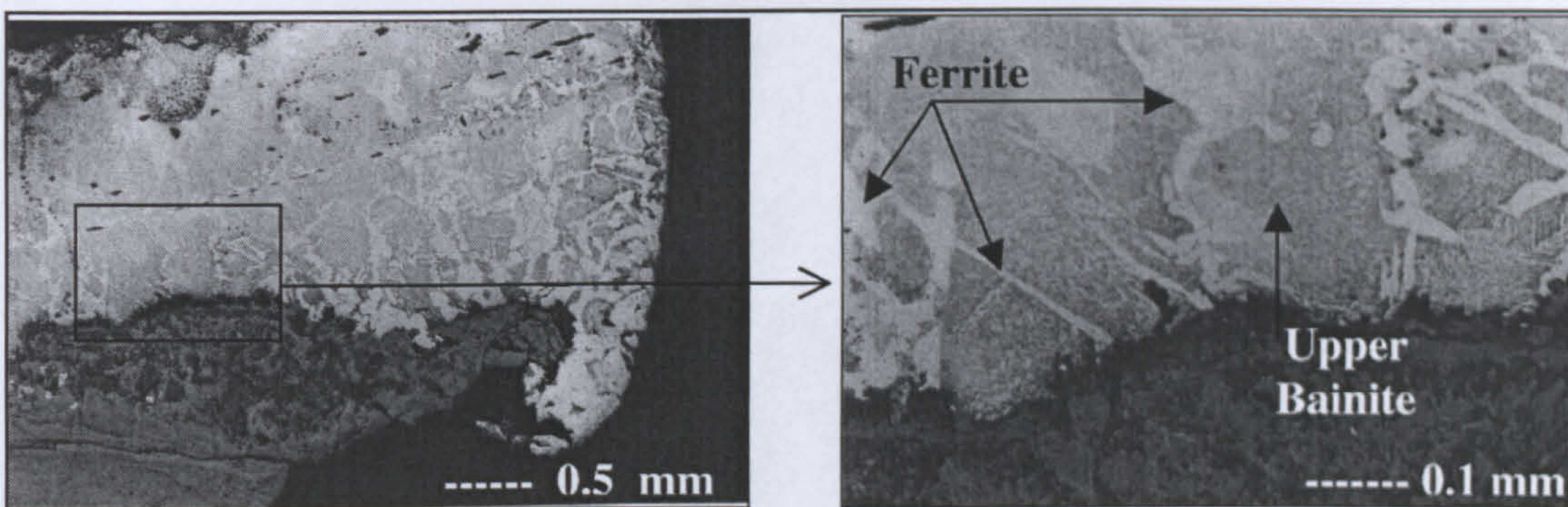


Figure 139b: Detail.

The gold applied to the sword was attached with adhesive during modern reconstruction. The gold sheet may be from a scabbard, which deteriorated during burial. The microstructure is composed of large areas of upper bainite with lathes and plates of ferrite indicating

JUM # 7

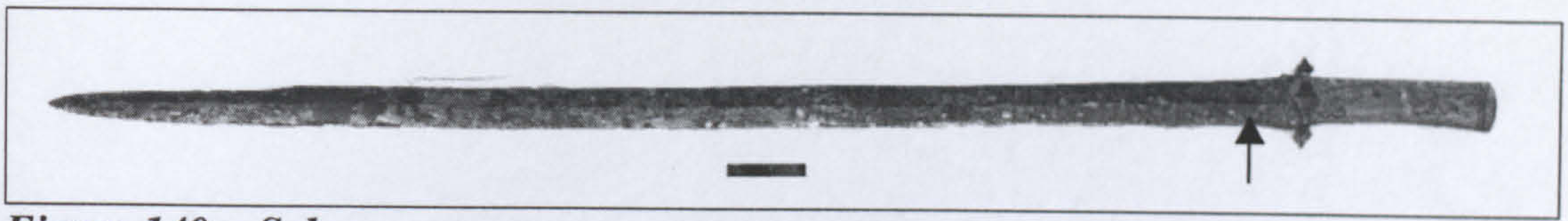


Figure 140a: Sabre.

JUM #	Length	Width	Thickness
7	91 cm	3.5 cm	0.5 cm

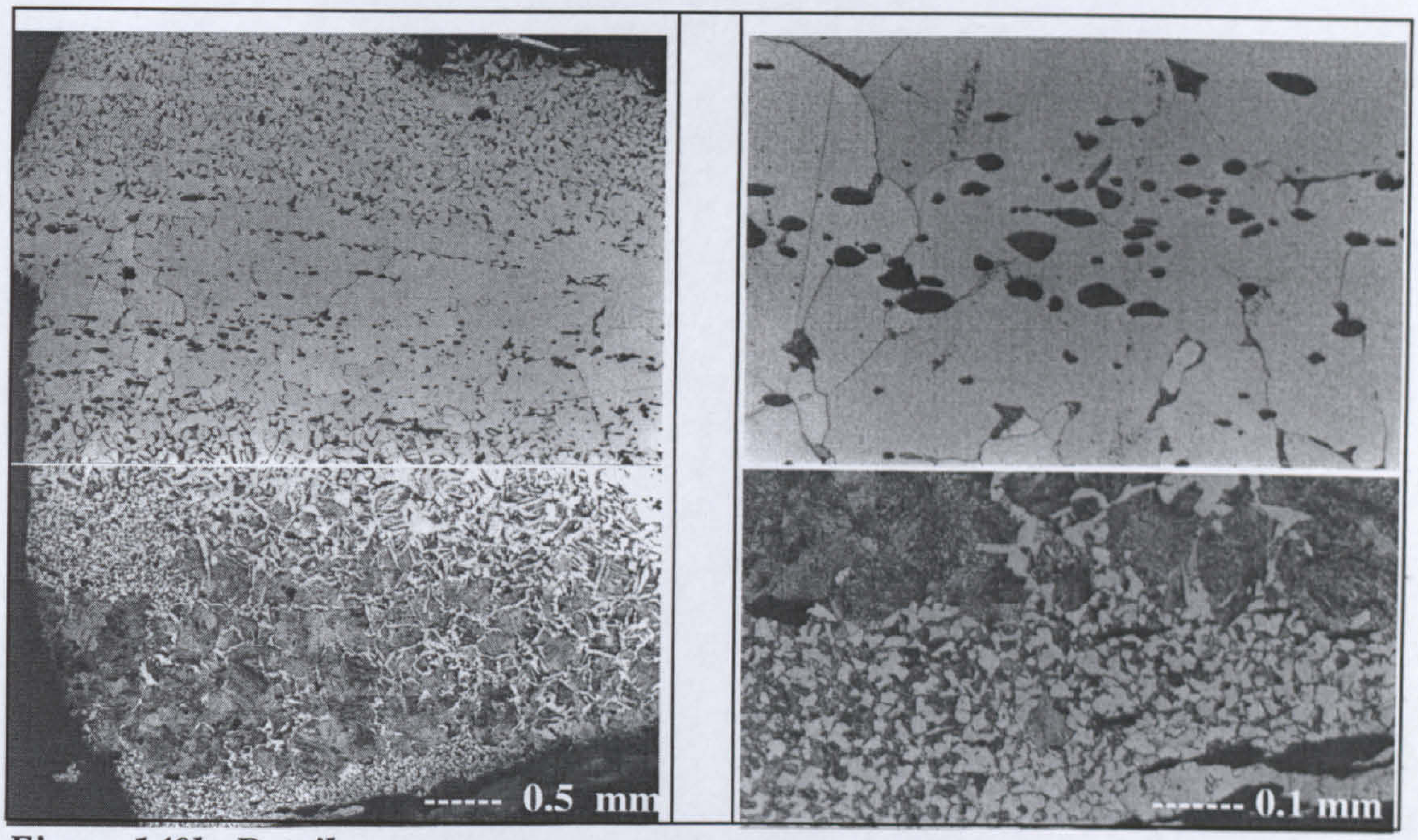


Figure 140b: Details

The sabre is composed of layers of steel welded onto an iron layer in the centre of the blade. Elongated slag inclusion can be observed in the iron and steel layers and at the boundary between them.

JUM # 8

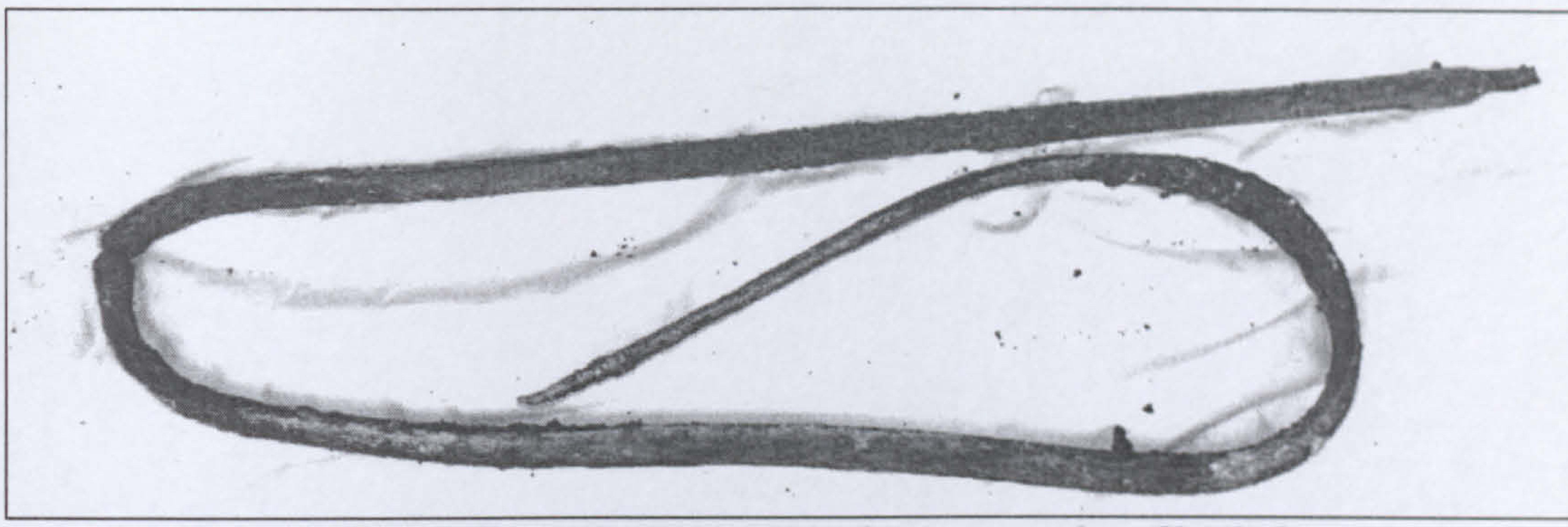


Figure 141a: Sabre ritually "killed". Detail of area near handle (below).

JUM #	Length	Width	Thickness
8	89 cm	3 cm	1 cm

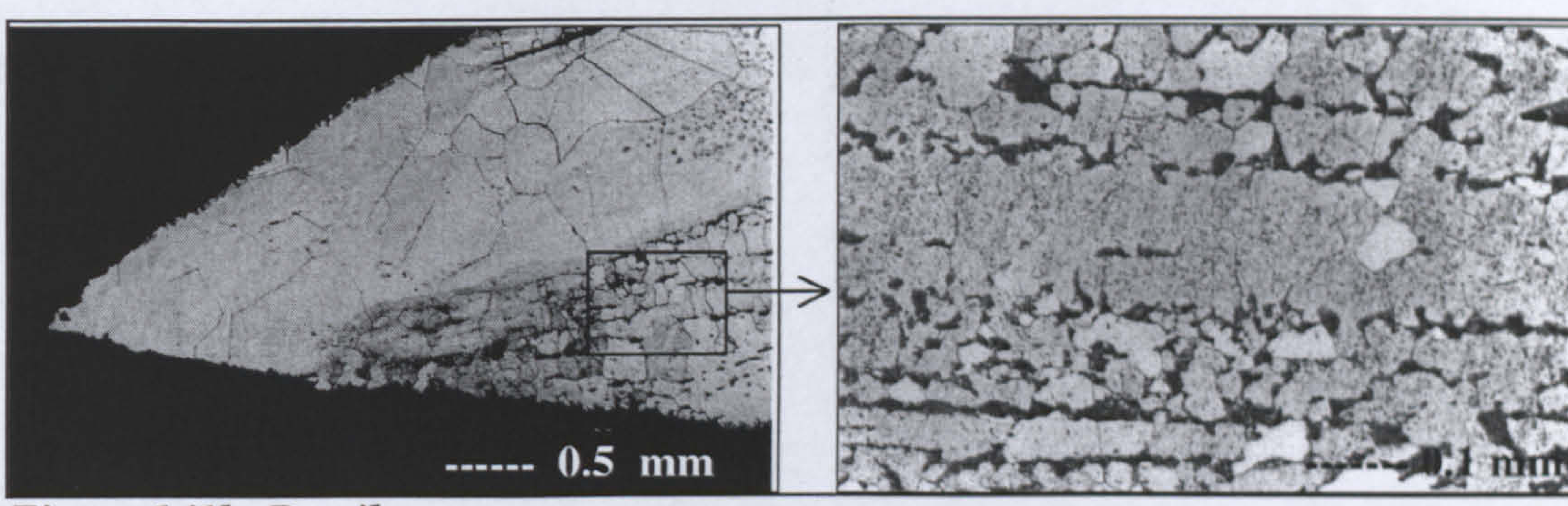


Figure 141b: Detail.

The sabre was ritually bent before being buried. The style of the attachment near the handle is also found on 10^{th} –12^{th} century AD Kirghiz swords (Nicolle, 1999, 290 and 477) and sabres from the western Steppes dated to 1150-1250 AD (Nicolle, 1999, 281 and 471). Its complex microstructure suggests that the sabre was used before being bent. The edge seems to be made of piled steel that was then forge welded onto an iron layer.

JUM # 9

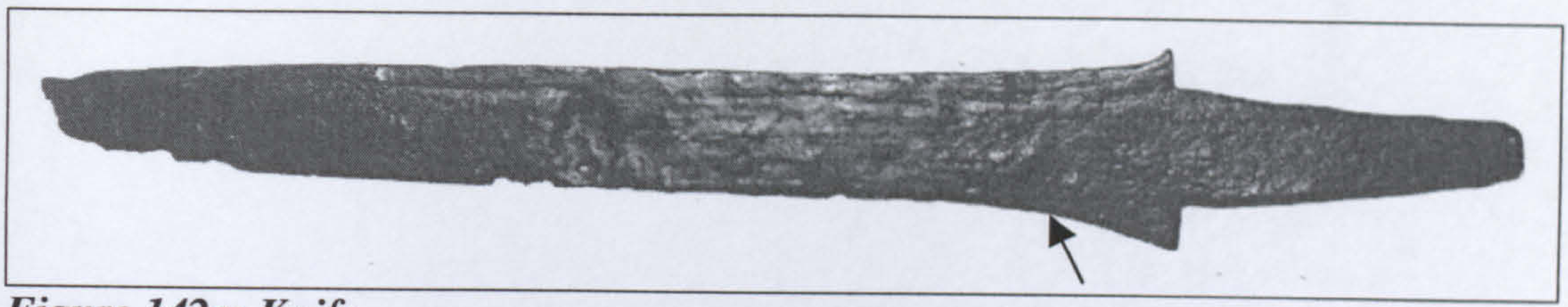


Figure 142a: Knife.

JUM #	Length	Microstructure
9	20 cm	Piled

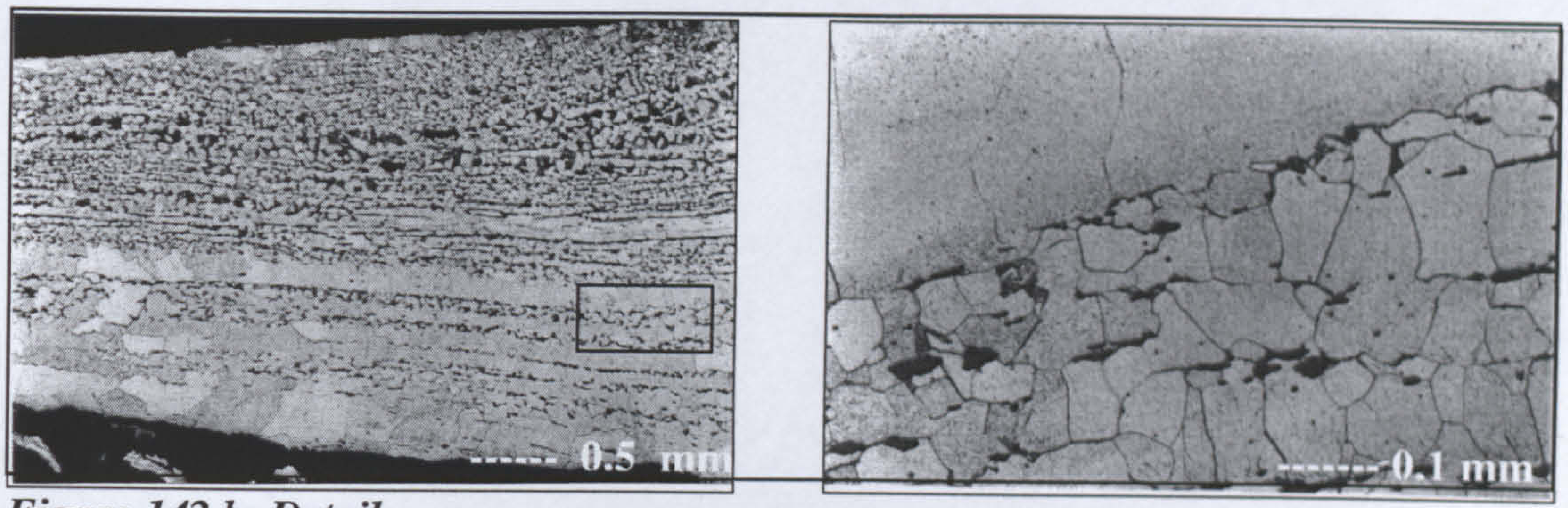


Figure 142 b: Detail.

The knife is composed of many layers of iron and steel.

JUM # 14

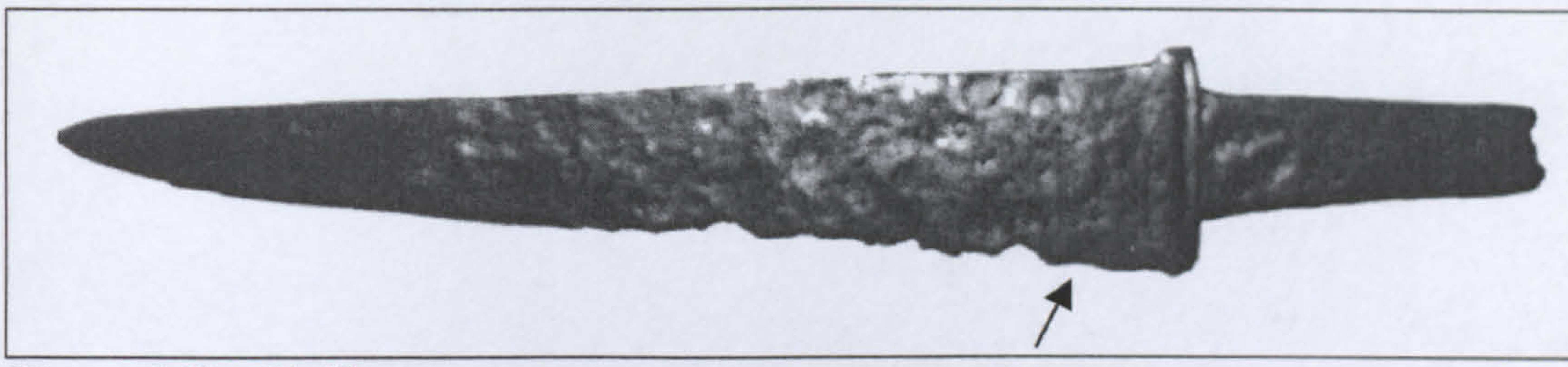


Figure 143a: Knife

JUM #	Length	Microstructure
14	17 cm	Layered

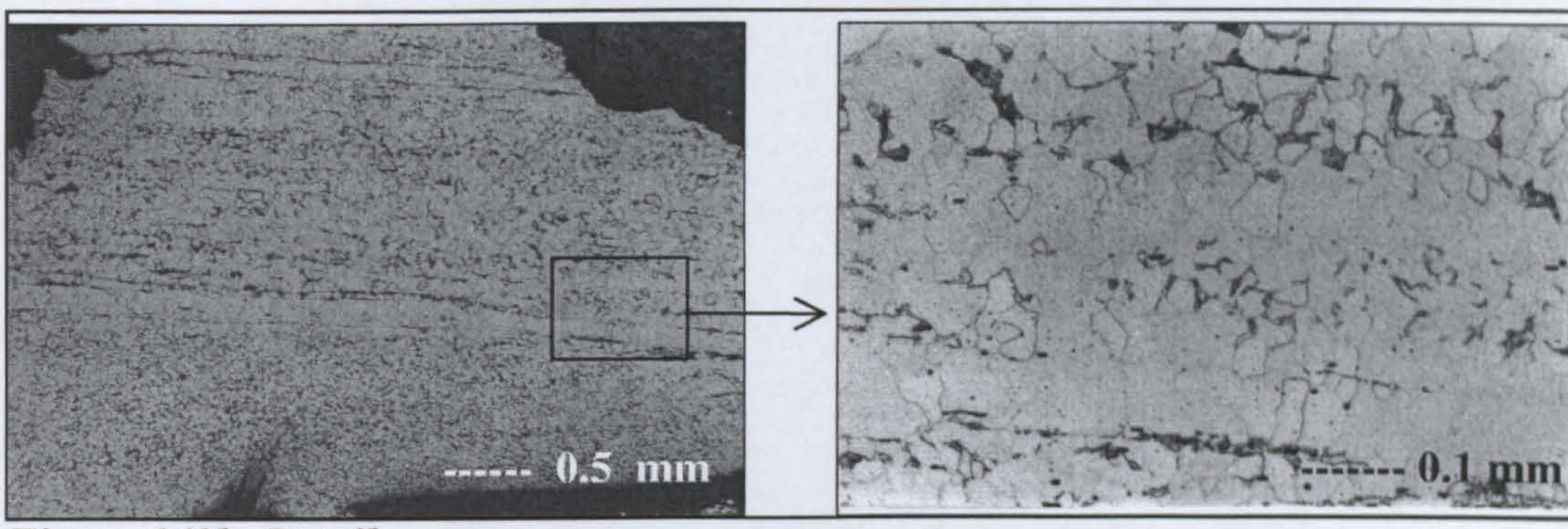


Figure 143b: Detail.

The sample is composed of layers of low carbon iron. Intergranular pearlite can be observed between the ferrite grains.

JUM # 15

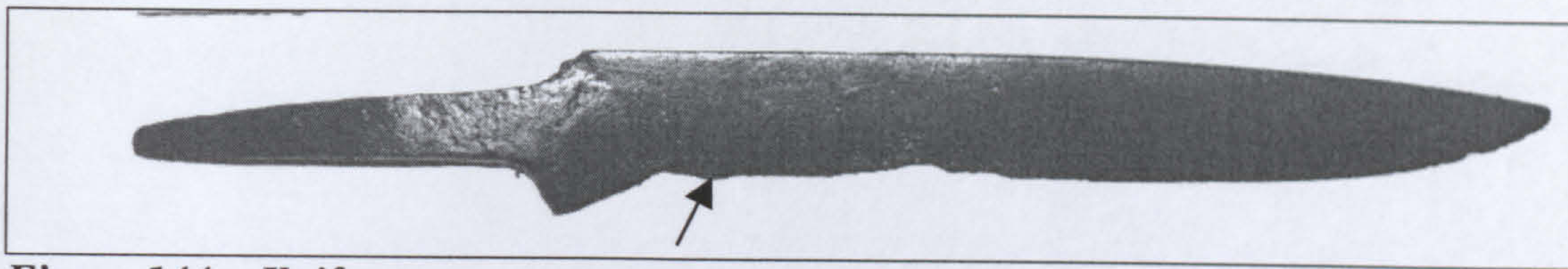


Figure 144a: Knife.

JUM #	Length	Microstructure
15	15 cm	Layered

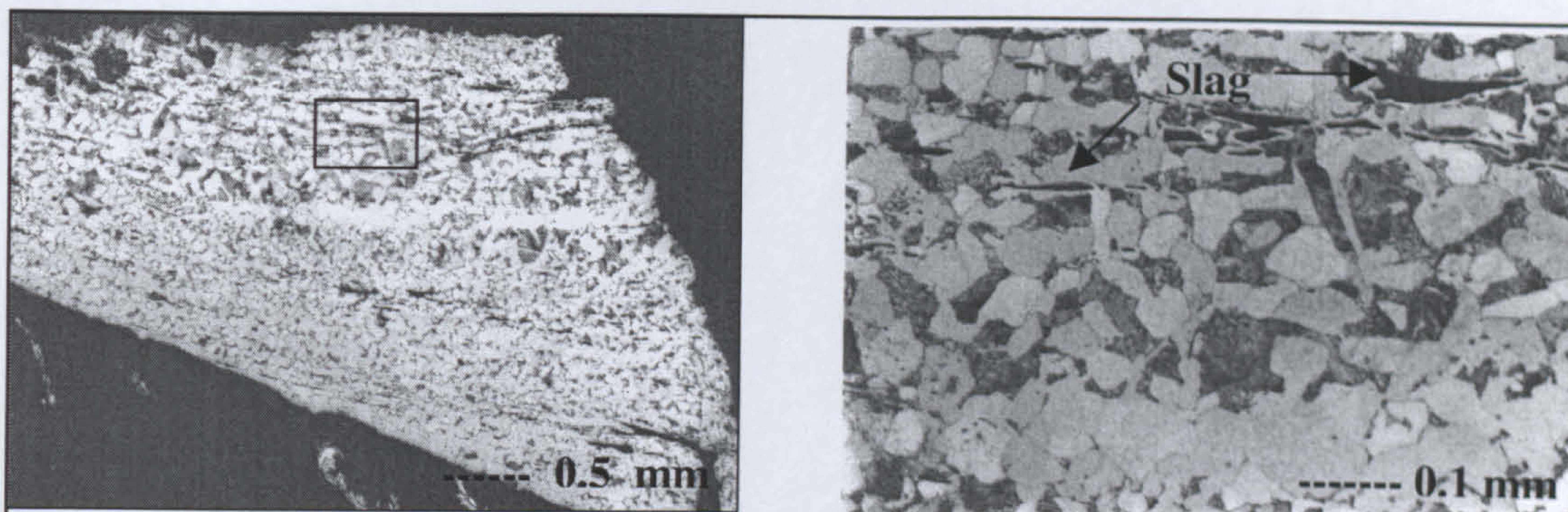


Figure 144b: Detail.

The blade is composed of layers of iron and steel. There are elongated slag inclusions within the steel.

JUM # 17

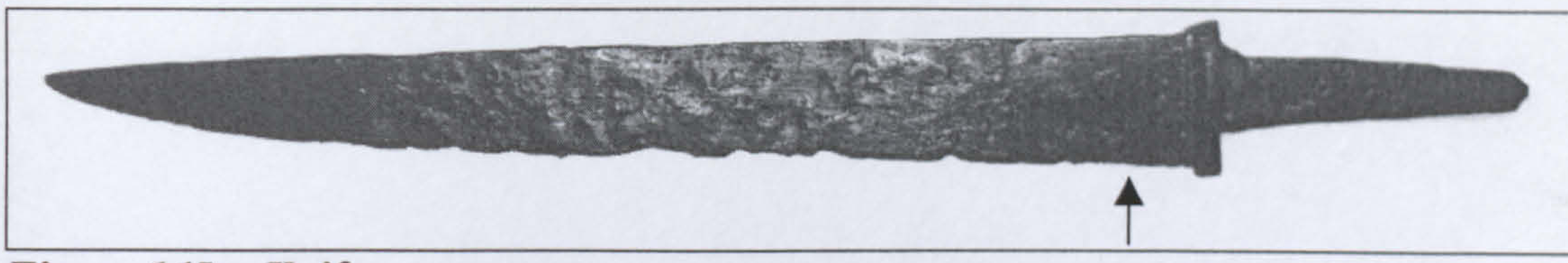


Figure 145a: Knife.

JUM #	Length	Microstructure
17	22.5	Layered

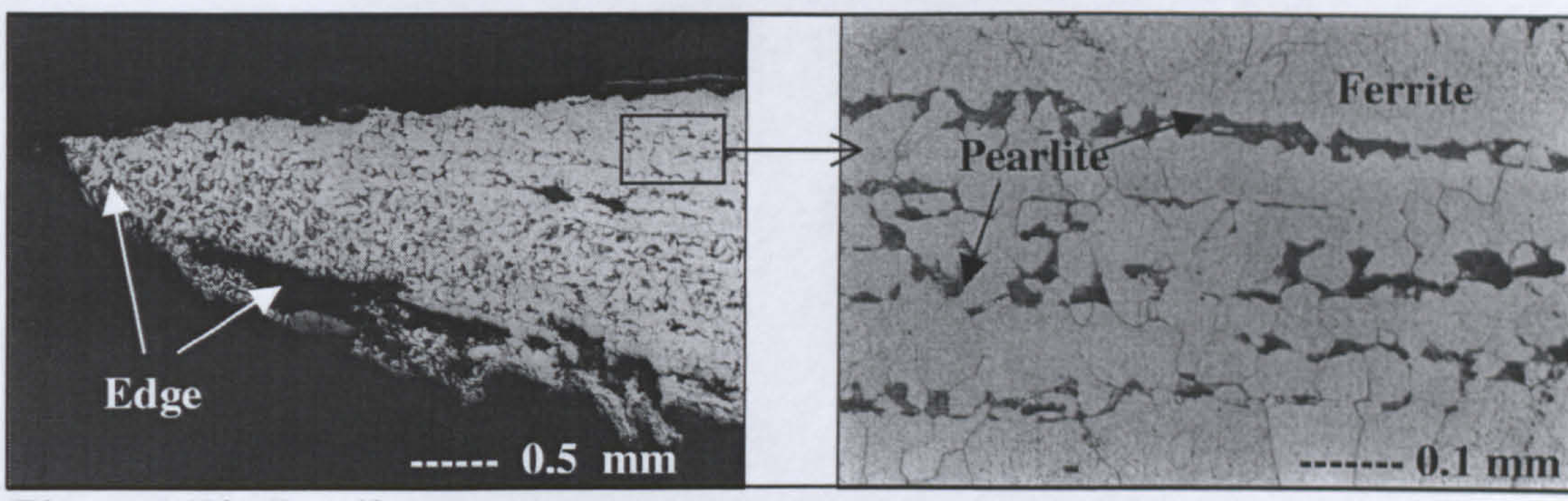


Figure 145b: Detail.

The knife is made of a series of layers of low carbon steel forge welded together. At the weld joins pearlite has accumulated producing bands at the forge line. A layer of steel was applied to the edge indicated by the higher proportion of intergranular pearlite to ferrite.

Kislovodsk # 1

UNK No.	Fe	Mn	S	Cu	Total
	93.6	0.2	0	0.08	94
	95.1	0.2	0	0.07	95.5
	96.8	0.2	0	0.08	**97.1**
inclusion	**40**	**20**	**19**	0	**79**

line scan	Fe	Mn	S	Cu	Total
1	95	0.5	0.4	0.08	**96**
2	93	0.3	0	0.07	**93.3**
3	95	0.3	0	0.08	**95.3**
4	94	0.3	0	0.09	**94.4**
5	95.7	0.3	0	0.09	**96.1**
6	94.5	0.3	0	0.12	**94.9**
7	90.9	0.3	0	0.1	**91.3**
8	94.7	0.3	0	0.1	**95.1**
9	92.7	0.3	0	0.08	**93**
10	95.2	0.3	0.3	0.08	**95.8**
11	94	0.3	0	0.08	**94.3**
12	95.4	0.3	0	0.07	**95.7**
13	92.5	0.2	0	0.07	**92.8**
14	95	0.2	0	0.07	**95.3**
15	94	0.2	0	0.07	**94.3**
16	93.6	0.3	0	0.08	**94**
17	92.7	0.3	0	0.1	**93.1**
18	94.5	0.3	0	0.1	**94.9**
19	95.4	0.2	0	0.09	**95.7**
20	95	0.3	0	0.08	**95.4**
21	95	0.3	0	0.09	**95.4**
22	95	0.2	0	0.07	**95.3**
23	95.8	0.2	0	0.06	**96.1**
24	94	0.3	0	0.07	**94.4**
25	95.8	0.3	0	0.08	**96.2**
26	95.2	0.3	0	0.07	**95.6**
27	96	0.2	0	0.09	**96.3**
28	95.2	0.3	0	0.08	**95.6**
29	95.8	0.3	0	0.09	**96.2**
30	96	0.3	0	0.08	**96.4**
31	95.3	0.2	0	0.08	**95.5**
32	95	0.2	0	0.09	**95.3**
average	**94.6**	**0.3**	**0**	**0.08**	**95**

slovodsk # 2 line scan

UNK No.	Fe	Cu	Total
1	100	0.1	100
2	99	0.1	99
3	100	0.1	101
4	100	0.2	100
5	100	0.1	100
6	98	0.1	99
7	95	0.0	95
8	100	0.2	100
9	99	0.2	99
10	95	0.0	95
11	96	0.1	96
12	100	0.2	100
13	95	0.1	96
14	100	0.2	101
15	100	0.2	100
16	93	0.0	93
17	99	0.1	99
18	99	0.1	99
19	101	0.2	101
20	96	0.1	96
21	98	0.1	99
22	100	0.2	100
23	100	0.1	100
Kis #2average	**98**	**0.1**	**99**

Kis 2 spot

UNK No.	Fe	Cu	Total
11	101	0.1	101
12	91	0.0	91
13	91	0.0	91
14	100	0.2	101

UNK No.	Fe	Cu	Total
tang			
9	96	0.3	96
10	95	0.2	95
12	98	0.2	98
13	95	0.9	96
14	95	0.2	96
15	96	0.2	97
average	**96**	**0.3**	**96**

:islovodsk # 10

UNK No.	Fe	Cu	Mn	Total
1	102	0.12	0	102
2	100	0.09	0	100
3	101	0.1	0	101
4	101	0.1	0	101
5	102	0.07	0.01	102
6	101	0.12	0.01	101
7	99	0.11	0.02	99
8	101	0.13	0.01	101
9	100	0.12	0	100
10	101	0.14	0.02	101
11	97	0.1	0.02	98
12	101	0.13	0.01	101
13	99	0.09	0	99
14	101	0.1	0.02	101
15	101	0.09	0	101
16	101	0.11	0.01	101
17	101	0.09	0.01	101
18	100	0.1	0.01	101
19	100	0.11	0	100
20	103	0.08	0	103
21	102	0.09	0.01	102
22	102	0.12	0.01	102
23	100	0.1	0	100
24	99	0.12	0	99
25	102	0.09	0.01	102
26	101	0.12	0	101
27	101	0.12	0	101
28	99	0.15	0.02	99
29	99	0.08	0	100
30	98	0.08	0.01	98
31	102	0.09	0	102
32	100	0.11	0	100
33	99	0.08	0.01	99
34	99	0.12	0.01	100
35	101	0.09	0.01	101
36	101	0.13	0	101
37	102	0.13	0	102
38	102	0.12	0.01	102
39	101	0.08	0.01	101
40	99	0.12	0.02	99
41	101	0.12	0.01	101
42	98	0.12	0.01	98
43	97	0.1	0.01	97
44	97	0.11	0.02	97
45	98	0.11	0	98
46	99	0.08	0.01	99
47	100	0.11	0	100
48	102	0.12	0.02	102
49	98	0.12	0.01	98
50	98	0.11	0	98

	Fe	Cu	Mn	Total
51	98	0.08	0.01	98
52	102	0.11	0	102
53	102	0.14	0.01	102
54	99	0.13	0.02	99
55	102	0.11	0.03	102
56	100	0.11	0	100
57	101	0.09	0.01	101
58	102	0.12	0	102
59	100	0.05	0.02	100
60	101	0.1	0.01	101
61	100	0.11	0.01	100
62	99	0.09	0.01	99
63	97	0.09	0.01	97
64	100	0.11	0	100
65	98	0.12	0.01	98
66	102	0.11	0.01	102
67	98	0.11	0.01	98
68	101	0.13	0.03	101
69	102	0.13	0.01	102
70	100	0.12	0.02	101
71	96	0.13	0.02	96
72	98	0.14	0	98
73	101	0.12	0.01	101
74	99	0.12	0.01	99
75	98	0.09	0.02	98
76	95	0.11	0.02	95
77	100	0.11	0.02	100
78	102	0.1	0.01	102
79	101	0.09	0	101
80	100	0.09	0.01	100
81	100	0.11	0.03	100
82	99	0.13	0	99
83	99	0.16	0.01	99
84	98	0.09	0	98
85	100	0.11	0.02	100
86	100	0.12	0	100
87	100	0.09	0.01	100
average	**100**	**0.11**	**0.01**	**100**

KIS # 10 spot

UNK No.	Fe	Cu	Mn	Total
6	94	0.01	0.01	94
7	100	0.13	0	100
8	99	0.09	0	99
9	99	0.1	0.02	99
10	94	0.01	0	94
11	100	0.14	0.02	100

Kislovodsk # 15 line

UNK No.	Fe	Cu	Mn	Total
1	101	0.00	0.03	101
2	98	0.02	0.02	98
3	100	0.03	0.01	100
4	99	0.00	0.02	100
5	102	0.01	0.02	102
6	102	0.01	0.01	102
7	101	0.01	0.01	101
8	102	0.01	0.01	102
9	102	0.01	0.03	102
10	102	0.00	0.01	102
11	102	0.03	0.01	102
12	102	0.00	0.01	102
13	100	0.03	0.01	100
14	99	0.00	0.02	99
15	99	0.00	0.03	99
16	100	0.00	0.02	100
17	102	0.00	0.02	102
18	100	0.01	0.03	101
19	100	0.02	0.03	100
20	100	0.00	0.01	100
21	99	0.01	0.03	99
22	99	0.00	0.02	99
23	100	0.01	0.04	100
24	99	0.00	0.02	99
25	99	0.00	0.02	99
26	99	0.00	0.03	99
27	99	0.01	0.03	99
28	99	0.00	0.01	99
29	101	0.01	0.00	101
30	101	0.00	0.01	101
31	99	0.01	0.02	99
32	100	0.01	0.01	100
33	100	0.00	0.01	100
34	100	0.01	0.02	100
35	99	0.00	0.03	99
36	99	0.00	0.02	99
37	99	0.01	0.03	99
38	99	0.01	0.00	99
39	97	0.00	0.02	97
40	98	0.00	0.01	98
41	100	0.01	0.00	100
42	98	0.02	0.01	99
43	99	0.00	0.02	99
44	100	0.00	0.01	100
45	98	0.00	0.02	98
46	99	0.01	0.03	99
47	97	0.00	0.03	97
48	101	0.00	0.01	101
49	101	0.00	0.00	101
50	100	0.00	0.01	100

UNK No.	Fe	Cu	Mn	Total
51	99	0.00	0.03	99
52	100	0.01	0.02	100
53	99	0.00	0.02	99
54	99	0.02	0.01	99
55	99	0.01	0.00	99
56	98	0.00	0.01	98
57	100	0.01	0.03	100
58	99	0.02	0.01	99
59	98	0.00	0.01	98
60	98	0.00	0.02	98
61	98	0.02	0.01	99
62	99	0.01	0.01	99
63	99	0.01	0.01	99
64	99	0.00	0.02	99
65	98	0.00	0.01	98
66	99	0.00	0.03	99
67	97	0.02	0.01	97
68	99	0.01	0.00	99
69	99	0.00	0.02	99
70	101	0.01	0.01	101
71	99	0.00	0.01	99
72	99	0.00	0.02	99
73	98	0.02	0.01	98
74	99	0.00	0.03	99
75	99	0.00	0.01	99
76	99	0.01	0.04	99
78	89	0.00	0.02	89
79	93	0.00	0.01	93
80	94	0.00	0.03	94
81	99	0.11	0.04	99
82	100	0.12	0.02	100
83	99	0.12	0.03	99
84	99	0.09	0.04	99
85	99	0.12	0.03	99
86	97	0.09	0.03	97
87	98	0.10	0.07	99
average	***99***	***0.01***	***0.02***	*99*

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